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Holocene glacier variations at Tyndall Glacier area, southern Patagonia

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Abstract

Tyndall Glacier of Southern Patagonia Icefield, located at 51°16′S and 73°15′W, is the 8th longest glacier in Patagonia, with an estimated area of 355 km^2 and a length of 38 km. In the side-valley on the left bank of this glacier, four Holocene glacier variations are recognized for the first time in Patagonia. A first Neoglacial advance occurred at *ca.* 3600 yr B.P., which formed terminal moraines perched on a steep wall of the side-valley and distinctive lateral moraines on the flat ground in the southern area. A second Neoglacial advance occurred presumably at *ca.* 2300 yr B.P., and is represented by a conspicuous trimline on the wall of the side-valley and a very distinctive trimline marked on the flank of the lateral moraine of Neoglacial advance I in the southern area. Both trimlines are located just several meters below the moraine ridges/crests of Neoglacial advance I, indicating the similar magnitudes of Neoglaciation I and II. A third Neoglacial advance, distinguished by the different color and surficial materials of the terrain, occurred at *ca.* 1400 yr B.P. A fourth Neoglacial advance, the Little Ice Age advance, culminated at *ca.* A.D. 1700.

1. Introduction

Lying at the southern end of the Andes, the Patagonia Icefield is comprised of the Northern and Southern icefields with an area of about 4,200 km^2 (Aniya, 1988) and 13,000 km^2 (Naruse and Aniya, 1992), respectively (inset, Fig. 1). Although they occupy very important location for the understanding of the Holocene glacier variations at the global scale, only very few field works on this subject have been carried out (*e.g.* Nichols and Miller, 1951 ; Malagnino and Strelin, 1992, Marden, 1993). Although Mercer (1965, 1968, 1970, 1976, 1982), after extensive collection of samples for radiocarbon dating, has established a scheme of the Holocene glacial chronology of Patagonia, in which three Neoglaciations, 4500－4000 yr B.P., 2700－2000 yr B.P. and 18th－19th centuries, are identified, few studies have tested the validity of this scheme. As recent variations of Patagonian glaciers suggest that they are highly localized due to topo-climatic effect (Aniya and Enomoto, 1986 ; Aniya, 1988 ; Aniya and Skvarca, 1992 ; Aniya *et al.*, 1992 ; Warren and Sugden, 1993), the earlier Holocene variation may also have been very localized. Consequently, it is still necessary to study glacial landforms around each major glacier and collect samples for dating from which to establish local glaciations. Only after the accumulation of such studies, it would become possible to elucidate a whole picture of the glacial chronology in Patagonia.

Tyndall Glacier is one of the major outlet glaciers of the Southern Patagonia Icefield (SPI, Hielo Patagónico Sur, Fig. 1). In order to elucidate the Holocene variation of Tyndall Glacier, we collected wood and organic samples for radiocarbon dating in 1990 and 1993 in the valley located on the east side of the glacier, into which two side-lobes once spilled out extensively. These samples have given absolute ages to episodes in the glacial chronology which are hitherto totally unknown in the southern part of the SPI. In the laboratory, digital photogrammetric mapping was carried out using aerial photographs to produce layers of contours and other important geomorphic features, on which field data were plotted. The objectives of

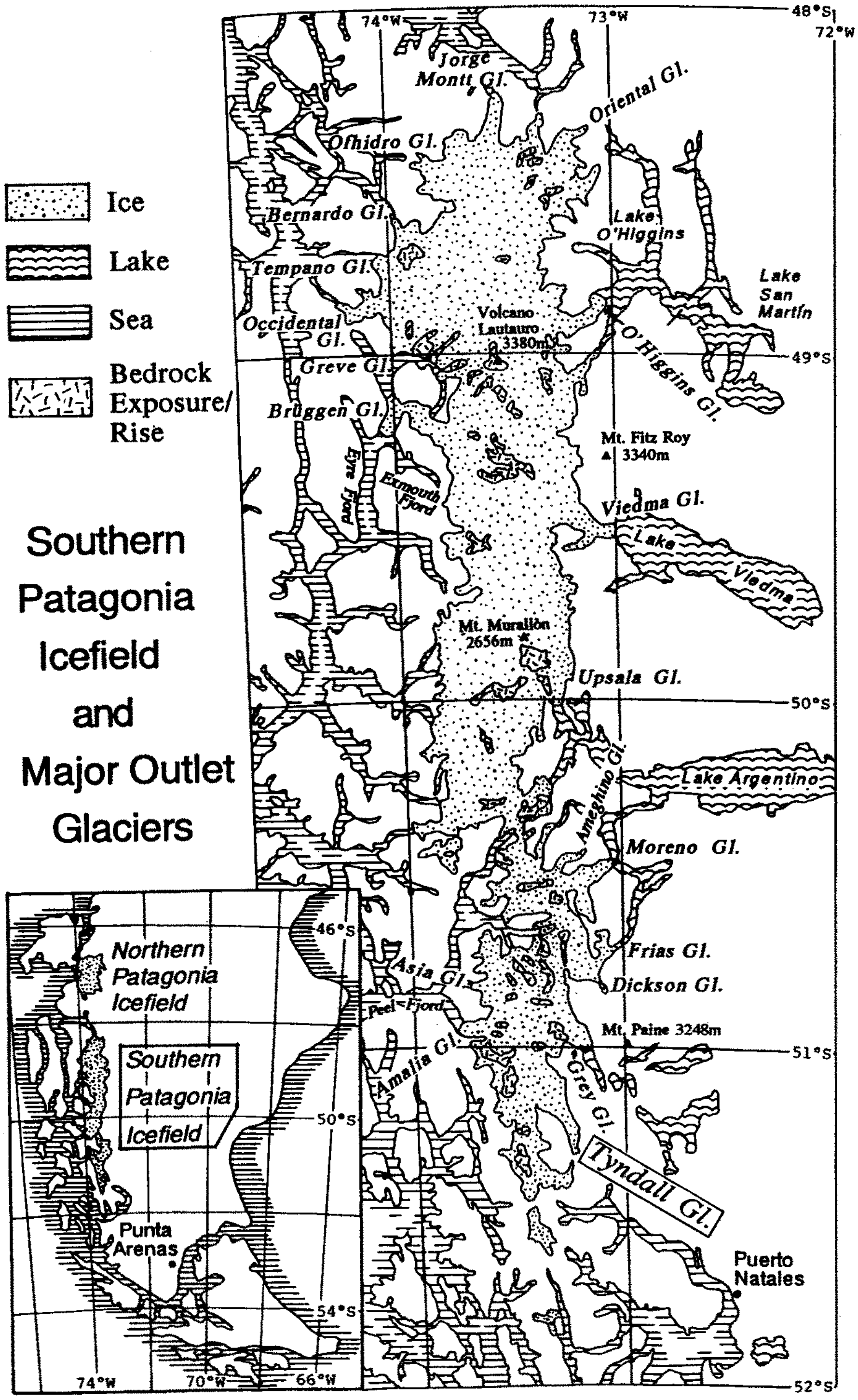

Fig. 1. Southern Patagonia Icefield and location of Tyndall Glacier. Map modified after Lliboutry (1956). Elevations of Co. Murallón and Co. Paine Grande are taken from topographic maps published by Argentinean and Chilean Governments, respectively.

this study are, therefore, first to describe glacial landforms in general using geomorphological maps and second to postulate the glacier variation based on the radiocarbon data.

2. Study area

Located at the southern end of the Southern Patagonia Icefield, Tyndall Glacier is currently terminating at around 51°16′S and 73°15′W. It is the 8th longest glacier in the Patagonia Icefields (Lliboutry, 1956), with an area of about 355 km² and a length of some 38 km (Naruse *et al.*, 1987). About 18 km upstream from the current snout, two small side-lobes on the left bank are slightly spilling into the eastern side valley. This side-valley is a through valley, running almost parallel to the glacier flow direction and opening north into the flood plain of Rio (River) Pingo and south to Laguna (Lake) Ferrier through an almost imperceptible divide. The area between the Rio Pingo flood plain and Laguna Ferrier was investigated, with detailed work in the area north of 1125 m peak (Figs. 2 and 3). In front of the lobes are located numerous terminal moraines with relatively fresh appearance, and the area west of Laguna Ferrier is lined by several rows of lateral moraines. A very distinctive characteristic of the area is that there are very clear, distinctive trimlines on the flank of mountains (Fig. 4, indicated with a) and moraine ridges (Fig. 5).

Rocks in this area are mostly interbedded shale -mudstone-sandstone of Cretaceous age (Servicio Nacional de Geología y Mineria, 1982). In few parts they are metamorphosed to phyllite. A simple monoclinal structure, dipping slightly to the east, dominates this area. Joints running roughly W-E, NE-SW and NW-SE are well-developed, which were exploited by the glaciers and became in places deep ravines.

3. Digital photogrammetric mapping

Utilizing vertical aerial photographs taken in 1975 at a nominal scale of about 1 : 87,000, and control points taken from the topographic map (Quadrangle, Rio Serrano), digital photogrammetric mapping was carried out on a Zeiss Planicomp P3 equipped with a modified AutoCAD program at a scale of 1 : 25,000, with a contour interval of 10 or 25 m depending upon the ruggedness of the terrain. On this map geomorphic features were plotted during the second field season in 1993. Due to the nature of the control points, absolute accuracy may not be good (probably on the order of a few meters) ; however, relative accuracy is much more important for this study. At the same time of the contour mapping, photointerpretation was also carried out for trimlines, distinctive moraines, lineations, terraces and other distinctive features, which were stored as separate overlays in digital forms. Using this map as a base, detailed landforms were plotted together with the results of the field survey to produce a geomorphological map of the area (Fig. 6).

4. Glacial landforms

Since the area north of 1125 m peak has been mapped and studied in great detail, the description of the glacial landforms is divided into the areas north and south of 1125 m peak.

4.1. Area north of 1125 m peak

Moraines, trimlines, outwash flats, proglacial lake-sediment flats, and lake strandlines are features associated with glaciation (Fig. 6). On the basis of the surficial characteristics, the valley can be divided into two areas, probably corresponding to the lobes (northern or southern) that covered the area. The area probably occupied by the northern lobe is generally covered by thick sediments/deposits with small shear moraines (Bishop, 1956) on top of them. Topography here is best described as step-like. On the other hand, in the area supposedly covered by the southern lobe, the bedrock is widely exposed with a veneer of lodgement till and erratics, and there are a few distinctive moraine ridges, some comprised of boulders with diameters in the range of 1−2 m. They are mostly shear moraines as rocks are round to subround. Boulders and gravel in most tills are typically subround, indicating strong influence of running water. Where the valley becomes confined toward the south (NE of 1125 m peak), a series of proglacial lake-sediment flats/terraces abut moraine mounds and are sometimes topped with moraine ridges, somewhat similar to the area covered by the northern lobe.

The northern part is characterized by stepped topography, in which three major levels of flat surfaces and four major moraine ridges are located, with steps and levels composed of moraines and outwash/ lake sediments, respectively (Figs. 6 and 7). This stepped topography was produced by the intermittent

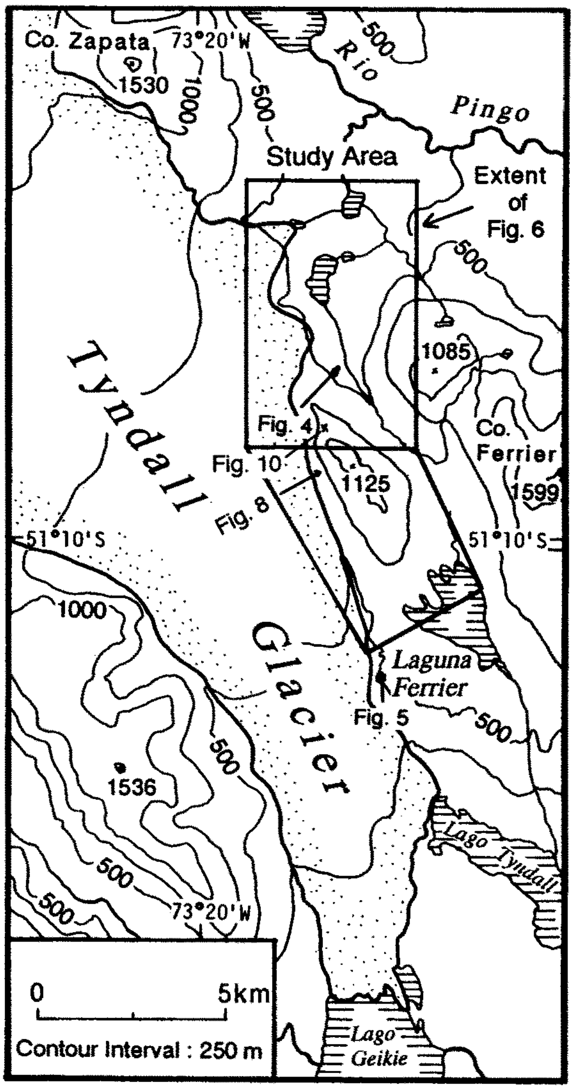

Fig. 2. Study area at the Tyndall Glacier area. Map based on 1 : 100,000 topographic map quadrangle "Rio Serrano" published by Instituto Geográfico Militar of Chile. Photographic points of Figs. 4, 5, 8 and 10 are indicated. The top rectangle is the extent of Fig. 6.

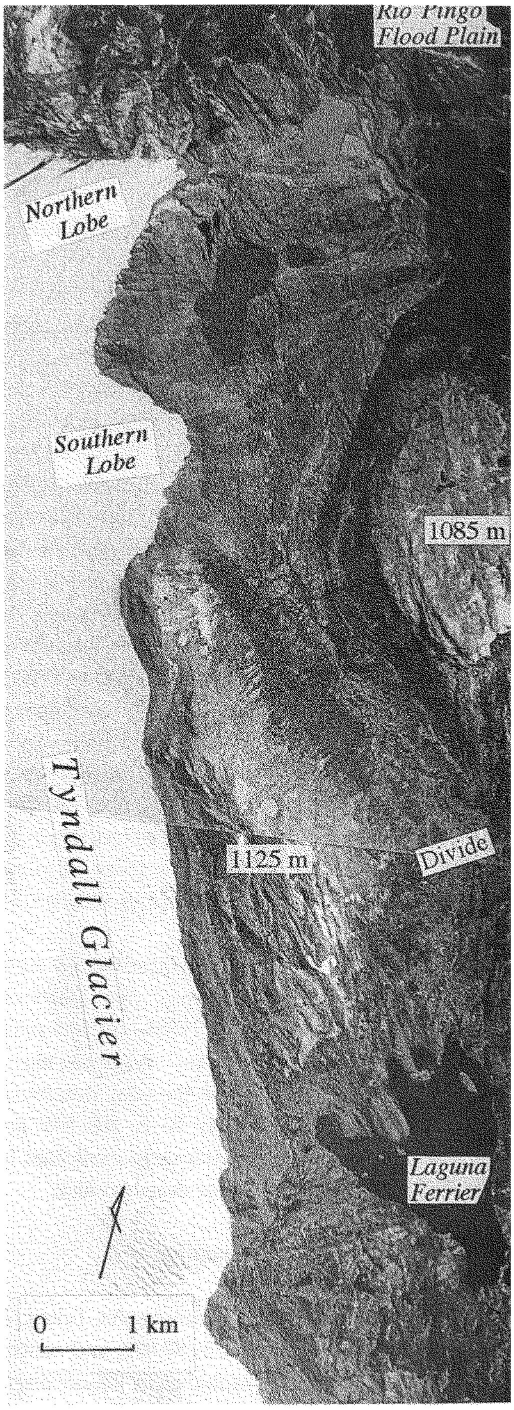

Fig. 3. Uncontrolled mosaic of aerial photographs (1975) showing Tyndall Glacier and the study area. Note : clear trimlines running on the northwest flank of 1085 m peak and on the west of 1125 m peak. Linear feature on the southwest flank of 1085 m peak is an old strand line.

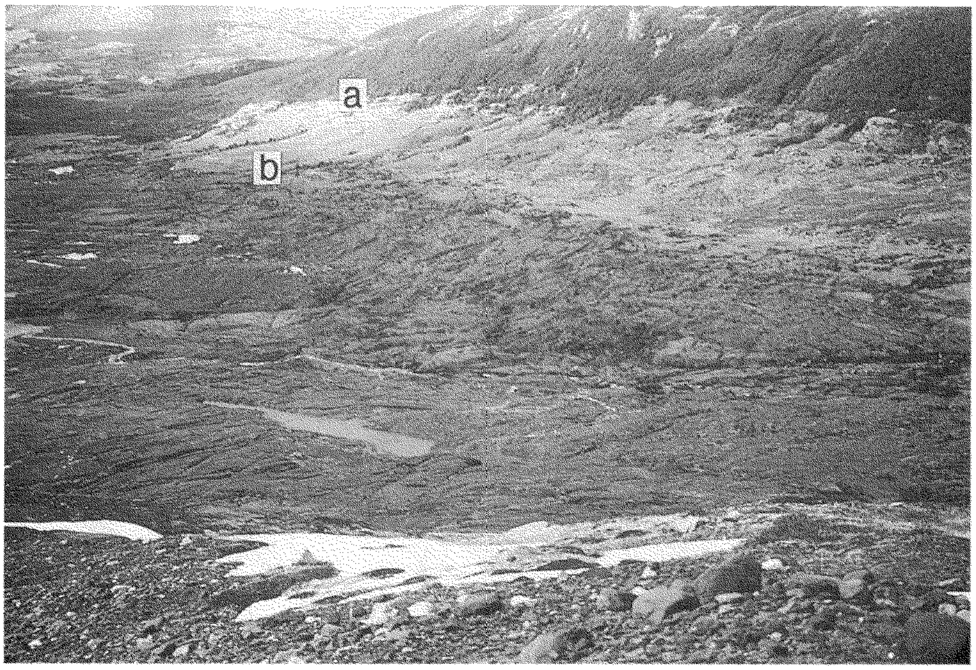

Fig. 4. Trimline (a) on the northwest flank of 1085 m peak , and the terrain coloration line (b) where the hillslope meets the valley bottom.

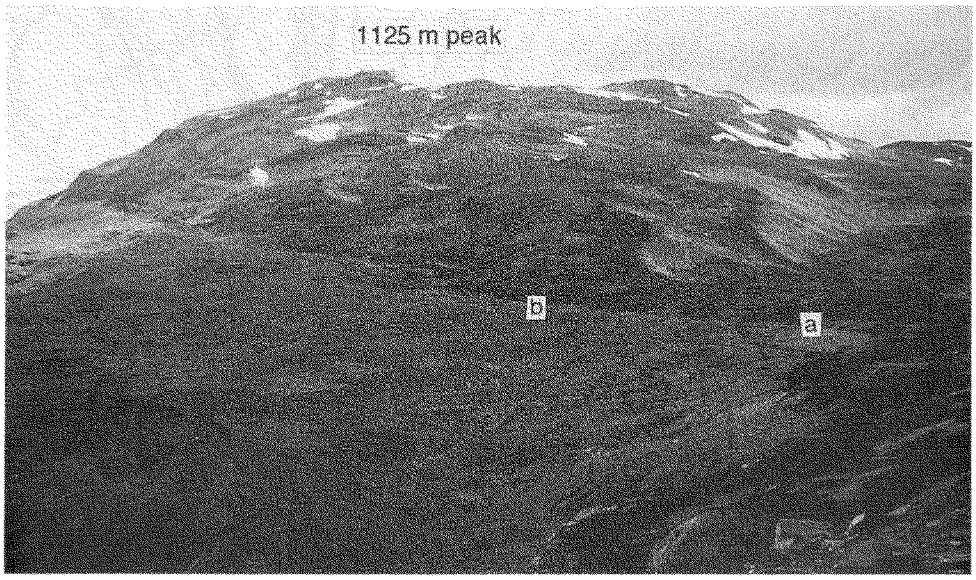

Fig. 5. Trimline (a) and lateral moraines, south of 1125 m peak. Just below the trimline etched on the flank of the lateral moraine, terrain coloration (b) can be discernible.

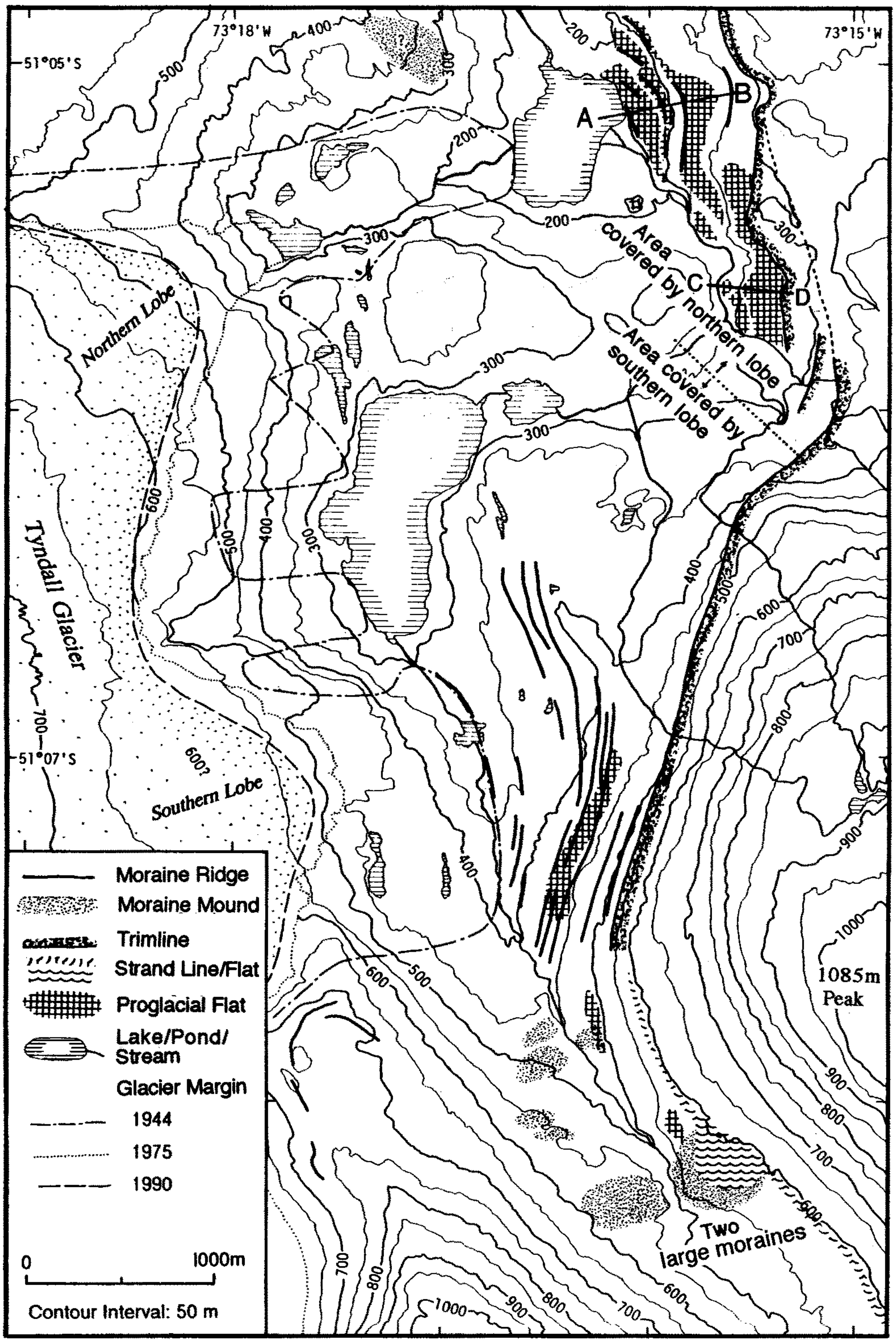

Fig. 6. Geomorphological map of the area, north of 1125 m peak. Locations of profiles shown in Figs. 7 and 11 indicated.

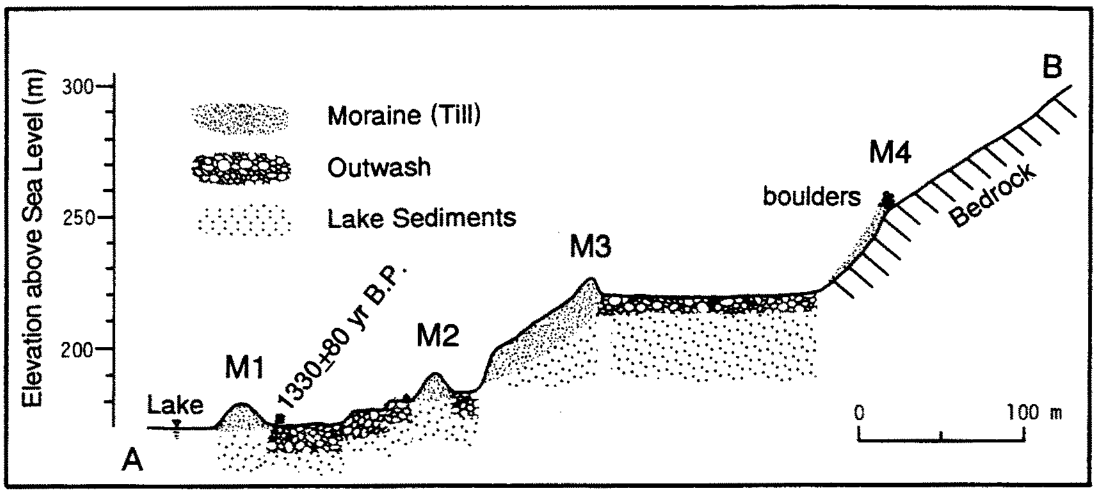

Fig. 7. Schematic profile of the stepped topography along line A-B in Fig. 6. Vertical exaggeration : 1.6x.

retreat of the northern lobe of Tyndall Glacier. Moraine ridges are comprised of well-sorted, subround/round boulders, gravel and sand of plutonic rocks, indicating strong work by running water. They are distinguished from younger to older as M1, M2, M3 and M4 for the sake of description. The topmost M4 consists of granitic gravel and a few boulders, which have been deposited on top of till and on bedrock. The outwash plain between M4 and M3, the third level, is wide and the eastern half is covered by a stand of *Nothofagus* whose ages are up to about 50 years. The outwash plain between M3 and M2 is generally narrow, probably due to a small amount of the recession. The plain between M2 and M1 is comprised of three minor levels with several small moraines on top, indicating minor halts during the recession.

In the southern part, a well-marked trimline is located on the northwest flank of 1085 m peak (Figs. 3 and 4). Only several meters above this trimline, patches of moraine ridges are perched on the hillslope which are generally covered with soil and thick forests of large *Nothofagus*. The depressions between these moraine ridges and the hill slope are 2–4 m deep and up to several meters wide. Below this trimline is bare bedrock (shale, mudstone, sandstone) with heavily frost-shattered surfaces, on which striations running about 75–255° are still visible.

Another demarcation line can be recognized about 100 m or so below this trimline, where the hillslope meets with the valley bottom surface (Fig. 4, indicated with b). Because of the different lithologies of erratics and till, the upper part is light while the lower part is dark. This demarcation line continues to another trimline and also to relatively level surfaces to the north, indicating that this line represents another glacial limit.

A very distinctive strand line/terrace is located at an elevation of about 600 m on the eastern side-wall of the valley for about 3 km near the southern end (Figs. 3 and 6, SW of 1085 m peak). Here the valley bottom is about level at elevations of 545–550 m. The valley bottom is underlain by clayey and silty sediments up to a few meter thick. The terraced area is very soggy with seeping water and the vegetation is noticeably different between above and below this terrace. On the western side wall, there is no terrace ; however, noticeable changes in vegetation can be recognized at the similar elevation of about 600 m. From these features, it seems certain that this area was once covered by standing water.

Two large moraines (labeled so in Fig. 6) once delimited the northern end of this once water-impounded basin. They are about 50 m high and 270–470 m wide, and are composed of round gravel and boulders. It is certain that these two moraines were originally a single ridge, but subsequently was cut into two by an overflowing stream. This moraine was formed in the valley where two glacier tongues once met ; one from the Co. (Mt.) Ferrier area, and another from Tyndall Glacier. When the climate ameliorated, the alpine glaciers nourished on the Co.

Ferrier area quickly disappeared, while the icefield -fed glaciers decayed slowly. As a result, the area once occupied by the alpine-fed glaciers became a lake, whose north end was blocked by the southern lobe of Tyndall Glacier, draining to the south through a divide (elevation about 600 m) in the through valley. During this period the strand line/terrace on the valley side and the strand flat at the top of the eastern big moraine were formed. With continued climatic amelioration, the surface of the glacier lobe became lower than 600 m ; however, the lake was retained for a while by the terminal moraine. Subsequent overflow initiated a stream which eventually drained the lake, leaving two separated terminal moraines.

4.2. Area south of 1125 m peak

Glacial landforms discussed in this section were all produced by and are located at the side of the main body of Tyndall Glacier. On the west side of 1125 m peak is located a trimline at elevations of about 750—600 m. About 15—20 m below this trimline is a clear demarcation line of different color of erratic/till, with the upper part much lighter (Fig. 8). The belt of light color is composed of whitish plutonic rocks with reddish weathering rind of 1 mm or so, and soil has formed at places with moss/grasses on. Below this demarcation line there are several rows of small lateral moraines and a conspicuous break of slope.

To the west of Lake Ferrier there is a row of very distinctive lateral moraines of about 10 m high from the surface level of the lake side. These moraines are covered with soils and thick vegetation. On the glacier side of these moraines is located a very distinctive trimline about 10 m below the moraine crest and below this trimline is a belt of white erratics of plutonic rocks (see Fig. 5). This trimline continues toward the glacier snout and can be seen on the flank of the terminal moraines semi-circling the proglacial lake Geikie. On the western side-wall of the glacier this trimline can also be conspicuously recognized.

5. Holocene glacier variations

As discussed above three distinctive demarcation features, a row of moraine ridges, trimline and terrain coloration line, can be recognized in this area along with numerous small moraines. On the basis of these geomorphic features and radiocarbon dates of several samples obtained in this study, reconstruction of glaciations in this area can be attempted (Fig. 9).

Two large terminal moraines located near the southern end of the valley and strand line/terrace at an elevation of about 600 m were probably produced during the last Pleistocene glaciation. A sample (NU -639) of wood piece was collected from a pit dug on the top surface of the eastern moraine and it yielded an age of 980±120 yr B.P. This date is widely off the time inferred from the circumstantial evidence of moraine formation, and because it is a piece of wood, this sample may be regarded as reworked one.

The first neoglacial advance is marked by terminal moraine ridges perched at spots on the hillslope

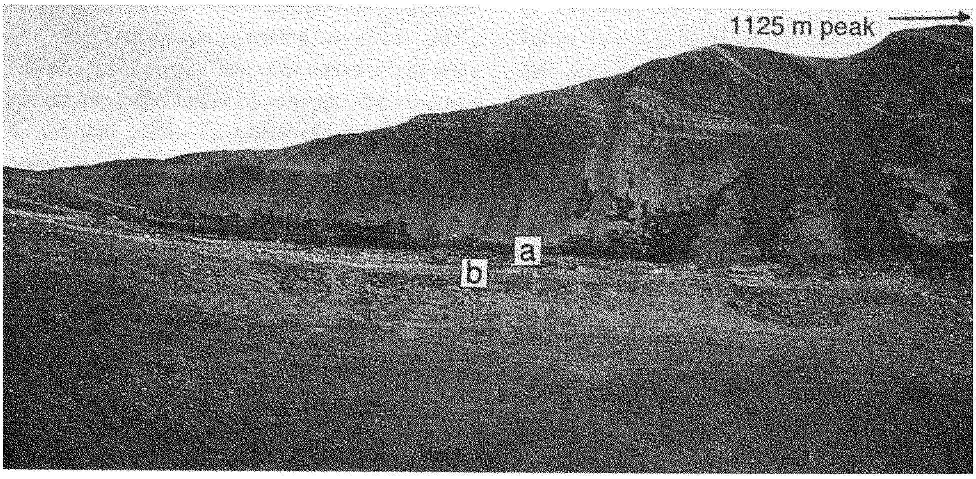

Fig. 8. Very distincitive trimline (a) and terrain coloration line (b), on the west flank of 1125 m peak. Vegetation lining above the trimline indicates the existence of lateral moraines.

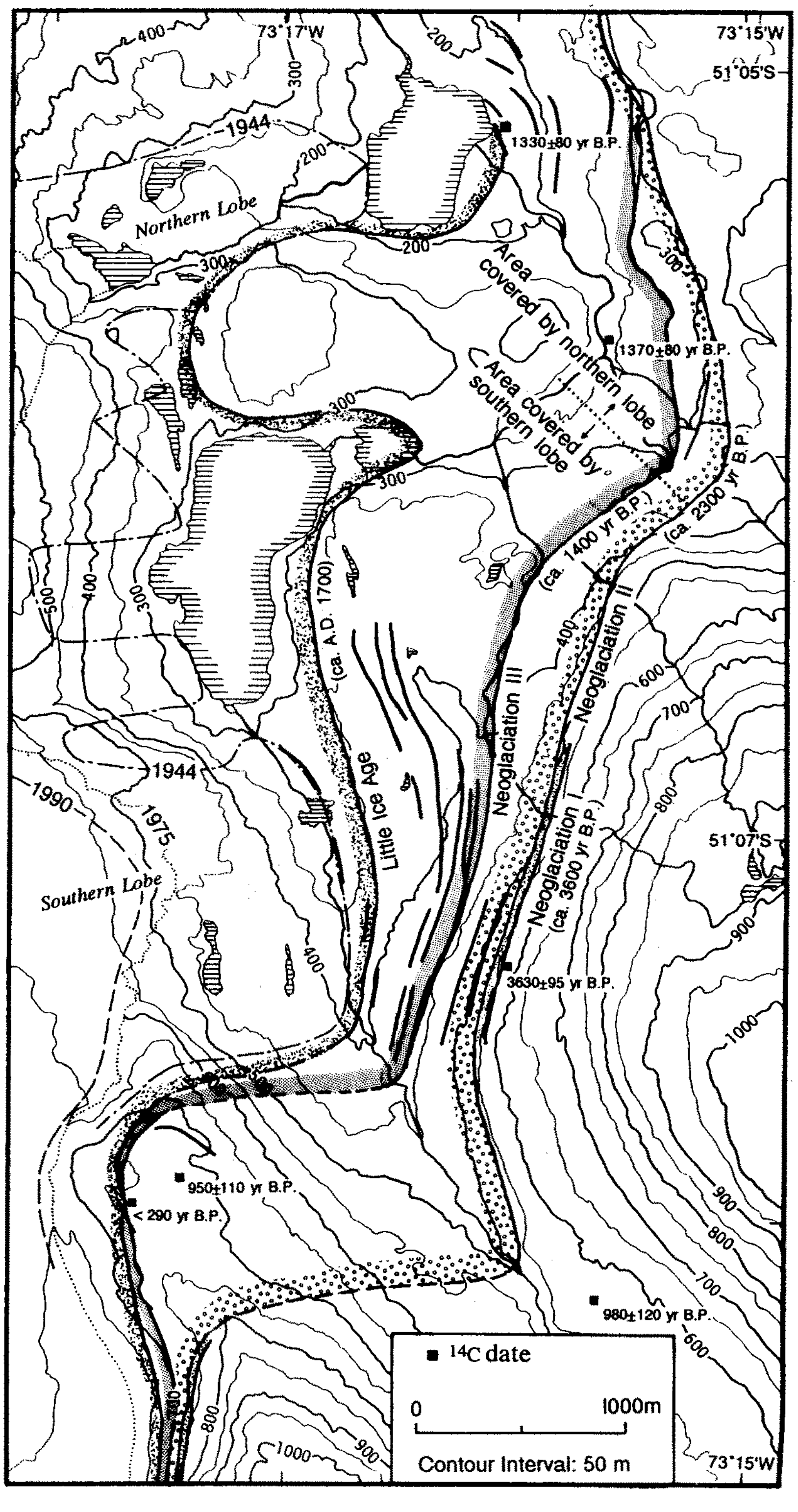

Fig. 9. Detailed map of Holocene glacier variations at the Tyndall Glacier area, north of 1125 m peak.

(area north of 1125 m peak), a continuous lateral moraine ridge located to the west of Laguna Ferrier (area south of 1125 m peak) and a semi-circular terminal moraine ridge around the present proglacial Lake Geikie. These moraine ridges are covered with well-developed soils and vegetation. An organic (peat?) sample (NU-640) was recovered from a depression located between the terminal moraine ridge and the northwestern hillslope of 1085 m peak and it is dated to be 3630±95 yr B.P. Since this depression was formed due to the moraine banking, this date indicates a minimum age of Neoglaciation I.

The second Neoglaciation is indicated by the conspicuous trimlines observed all over the area. The trimline is located only several to ten meters below the moraine ridges/crests of Neoglaciation I, indicating the similar magnitudes of two Neoglaciations. West of Lake Ferrier, this trimline is etched on the side of the Neoglaciation I lateral moraine (see Fig. 5), so is at Lake Geikie. In front of the southern lobe, this trimline is marked on the bedrock hillslope of 1085 m peak. Such two glacial advances of the similar magnitudes were reported at Upsala Glacier, which occurred at *ca.* 3600 yr B.P. and 2300 yr B.P. (Mercer, 1965, p. 411). Although Mercer was skeptical of the earlier advance of the two, the data at Tyndall Glacier confirms two such neoglacial advances of the very similar magnitudes. There is no dating for Neoglaciation II in the Tyndall Glacier area ; however, the resemblance of these two glaciations in the two areas strongly implies that Neoglaciation II in the Tyndall area also occurred at *ca.* 2300 yr B.P. as did in the Upsala Glacier area.

The date of the third Neoglaciation, around 1370±80 yr B.P., was obtained from a piece of wood (NU-356) collected from a *Nothofagus* standing dead on an exhumed surface in the stepped topography area of the northern part of the study area. This surface was once covered by sand which deposited in a proglacial lake and was subsequently exhumed by stream erosion. On this surface and even in the stream, there are a few broken but standing *Nothofagus* stumps whose DBH (Diameter at Breast Height) is up to 60 cm, indicating that there was once a stand of large *Nothofagus*. It was subsequently buried and killed by sediments in a proglacial lake formed by an advancing glacier. The surface level of the lake sediments is associated with the lower trimline (Fig. 10) that continues to the third distinctive demarcation line (terrain coloration). Another, similar date, 1330±80 yr B.P. , was obtained from a sample (NU-638) collected from a depression between M1 and M2 (see Fig. 7) ; however, the surface of the sampling site is much younger. Since this sample is fragments of wood there is a good possibility that this sample was reworked from a tree killed by the Neoglaciation III advance. In the Andes, the glacial advance during this period is reported only in Peru (Clapperton and Sugden, 1988). A sample (NU-636) collected from a depression between Neoglaciation II and III moraines on the north side of 1125 m peak gives an age of 950±110yr yr B.P. This date is incongruent with the other date. Since the sample is fragments of wood, this is probably due to rework. However, the similar dates of samples NU

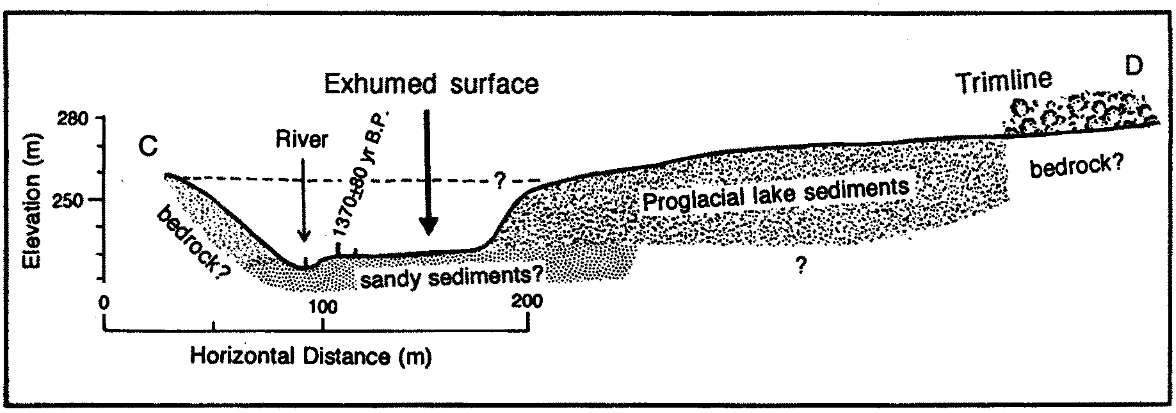

Fig. 10. Profile along line C-D in Fig. 6. Dead but standing *Nothofagus* are schematically depicted on the exhumed surface and in the river. Broken line supposedly indicates the surface level before stream erosion. Vertical exaggeration : 1.25x.

-639 and NU-636 suggest that some environmental changes occurred around A.D. 1000.

A fourth Neoglacial advance during the Little Ice Age culminated at *ca.* A.D. 1700 (NU-637). At the north side of 1125 m peak, this glacial advance left a moraine ridge very close to the limit of Neoglaciation III, only up to several tens of meters away. At one point it abuts the Neoglaciation II moraines, breaching the Neoglaciation III moraines. An organic sample (NU-637) was collected from a depression formed between the moraines of Neoglaciation II and IV, that yielded an age of younger than 290 yr B.P (Figs. 9 and 11). It seems that this glacial advance did not last long, because while the main body of the glacier had thickened to reach nearly the same level as Neoglaciation III, the duration was not sufficient for the spilling lobes to reach close to the maximum extent of Neoglaciation III on the bottom of the side-valley. MI is a single moraine ridge standing above the outwash plain, and it may represent the glacial advance during the Little Ice Age. Figure 12 summarizes those Neoglaciations around Tyndall Glacier.

6. Discussion

For the SPI, Mercer (1982) identified three Neoglacial advances at *ca.* 4500–4000 yr B.P., 2700–2000 yr B.P., and A.D. 1750–1800, from glaciers located on the northwestern side of the SPI. Clapperton and Sugden (1988) suggested a Third Neoglacial advance at 1300–1000 yr B.P., on the basis of data from the sub-Antarctic islands, thereby proposing four major Neoglacial advances for the Andes. The dates, 1370±180 yr B.P., and 1330±80 yr B.P. obtained in this study are the first ones in Patagonia which fit into this postulated third Neoglacial advance. The glacial advance dated *ca.* 3600 yr B.P. in this study supports the date that Mercer (1965) obtained but was skeptical of for Upsala Glacier.

For the first time in Patagonia, four Neoglaciation are recognized at the Tyndall Glacier area, confirming the model Clapperton and Sugden (1988) proposed for the Andes. However, the date of the First Neoglacial advance is different. There are no other glaciers in Patagonia at which more than three

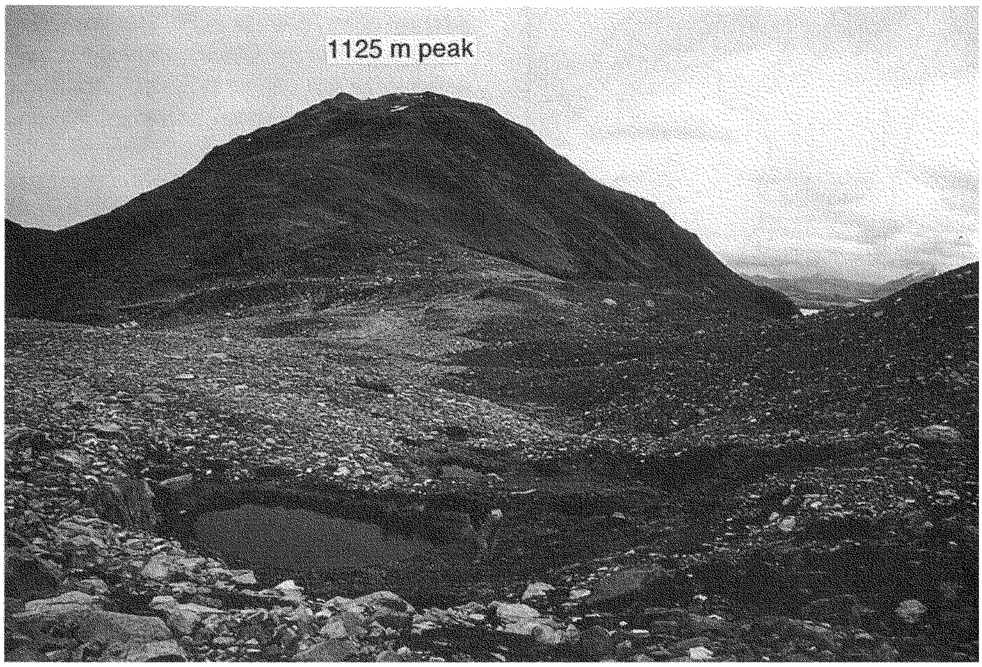

Fig. 11. Sampling site (NU-637, *ca.* A.D. 1700) of Neoglaciation IV, which breached the moraine of Neoglaciation III (right, dark till) and abuts the moraine of Neoglaciation II (left, red stained till). Just north of 1125 m peak at an elevation of around 750 m.

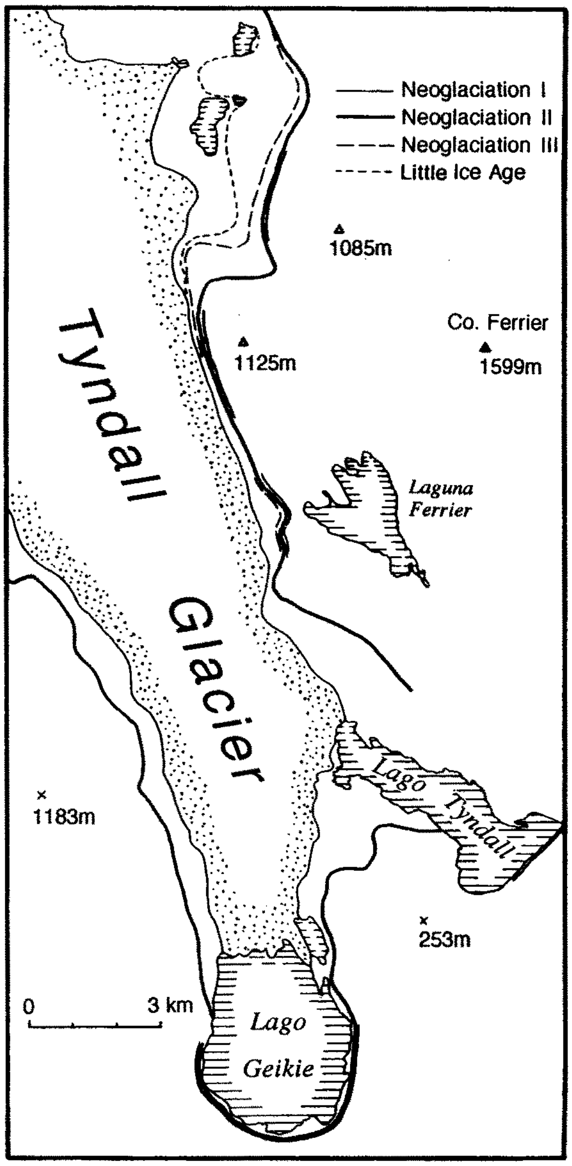

Fig. 12. Holocene glacier variations around Tyndall Glacier.

Neoglaciations have been recognized, except for Upsala Glacier where Mercer (1965) identified two certain (ca. 2300 yr B.P. and A.D. 1600) and one uncertain (ca. 3600 yr B.P.) glaciations. In the Upsala Glacier area, Mercer did not recognize a glacial advance of *ca.* 1400 yr B.P. ; however, two peat samples collected around Pearson I moraines of Upsala Glacier in 1993 yielded dates of 1430±155 yr B.P. (NU-634) and 1620±90 yr B.P. (NU-635) (Aniya and Sato, 1995). Few kilometers further down south of Pearson I moraine, there is another set of terminal moraines, which Malagnino and Strelin (1992) named Herminita moraine. The ages of the Herminita moraines are dated to be 2360±90 yr B.P. (NU-629) and 2180±125 yr B.P. (NU-630) ; the first date obtained by a peat sample recovered from a depression between the hillslope and a moraine ridge and the second date by another peat sample collected from a depression among moraines. These dates are the same as the age Mercer (1965) has given to Pearson I, which corresponds to the Second Neoglaciation in Patagonia. On the basis of these and other new datings, the Holocene variation of Upsala Glacier was revised (Aniya and Sato, 1995). Consequently, it appears that also at the Upsala Glacier area, four glacial advances occurred. It is interesting to note that the two glaciers, Upsala and Tyndall, which are located widely apart, fluctuated almost simultaneously during the Holocene. However, at Upsala Glacier, the first Neoglacial advance at *ca.* 3600 yr B.P. was less extensive than the second advance at *ca.* 2300 yr B.P. At Moreno Glacier, which is located between Upsala and Tyndall glaciers, Mercer (1968) reported that it remained smaller than it is today during the entire interval after 10,000 yr B.P. However, the age of the trimline at Moreno Glacier obtained in this study was dated to be 820±90 yr B.P. (NU-355), indicating that the glacier had reached its recent maximum around 12th century. This date is close to A.D. 1300±190 obtained for the initial stage of the Little Ice Age advance at Ofhidro Norte Glacier (Mercer, 1970).

7. Conclusion

From the detailed study of glacial landforms and radiocarbon dates, the Holocene glacier variations at Tyndall Glacier in the Southern Patagonia Icefield was postulated. This is the first such data from the southern half of the SPI. Four Neoglacial advances at *ca.* 3600 yr B.P., *ca.* 2300 yr B.P., *ca.* 1400 yr B.P. and *ca.* A.D. 1700 are recognized. The result at the Tyndall Glacier area, supported by new data from Upsala Glacier, suggests that four Neoglacial advances may have occurred at other glaciers in Patagonia, that can be revealed only by detailed field studies and extensive radiocarbon datings. The data from the Patagonia Icefield are still scarce, and we need many more data from various parts of the icefields before firmly establishing the glacier variations in Patagonia.

Acknowledgments

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