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Holocene glacial chronology of Upsala Glacier at Peninsula Herminita, Southern Patagonia Icefield

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Abstract

A new scheme of Holocene glacial chronology was presented for Upsala Glacier of the Southern Patagonia Icefield, South America. Five peat samples collected from moraines for ^{14}C dating were used to examine the Holocene glacial chronology established by Mercer in 1965. The new scheme proposed in this study calls for four Neoglaciations, Neoglaciation I, Herminita, Pearson I and Pearson II, and the change in the age assignment of the Pearson I glaciation. Although the existence of a first Neoglaciation at *ca.* 3600 yr B.P. was not directly confirmed by landforms and additional ^{14}C datings, because its extent was less than the second one, the ^{14}C data from other glaciers strongly suggest that there could have been a glacial advance at this date at Upsala Glacier. A second Neoglaciation, Herminita advance, which was first identified in 1990, was for the first time dated in this study to be *ca.* 2400−2200 yr B.P., agreeing well with other glaciers in Patagonia. A third Neoglaciation represented by the Pearson I moraines (with substages, a, b, c) occurred at least *ca.* 1600−1400 yr B.P., although it was long established to be *ca.* 2300 yr B.P. by Mercer. These dates are close to a third Neoglaciation proposed by Clapperton and Sugden in 1988 for the Andes. Since there is another date, *ca.* 900 yr B.P, which probably belongs to the Pearson Ic, the third glaciation may have lasted very long, close to 700 years, with oscillations. A fourth one, the Pearson II, is taken as the same as the Mercer's scheme, that is, A.D. 1600−1760.

1. Introduction

The Patogonia Icefield, comprising of the Northern Patagonia Icefield (NPI) and the Southern Patagonia Icefield (SPI), lies near the southern end of the Andes, South America (inset, Fig. 1). The Patagonia Icefields occupy an important place for the study of glaciology and glacial geomorhology/geology, because, with the combined area of about 17,200 km^2 (Aniya, 1988 ; Naruse and Aniya, 1992), they consitite the largest temperate glacier body in the southern hemisphere. However, very few studies on glacial geomorphology/geology have been carried out to elucidate Holocene glacier variations in this area (*e.g.* Nichols and Miller, 1951 ; Mercer, 1965, 1968, 1970, 1976 ; Malagnino and Strelin, 1992).

Upsala Glacier, located on the mid-east side of the SPI (Fig. 1), is one of the few glaciers where glacial geology has been studied. Mercer (1965) has identified two certain and one uncertain Neoglaciations in the Holocene. Two certain ones are called Pearson I and Pearson II, which occurred at *ca.* 2300 yr B.P. and during the Little Ice Age, respectively. The uncertain one was dated to be *ca.* 3600 B.P. Recently, Malagnino and Strelin (1992) have identified another distinctive set of moraines near the tip of the Peninsula Herminita stretching in front of Upsala Glacier, that represents an older glaciation than the Pearson I advance, calling them "Herminita glacial stage". However, no date was given.

During the field season of 1993, the authors collected several peat samples for ^{14}C dating from the Herminita moraines and the Pearson I moraines. These samples have yielded new dates to these glacia-

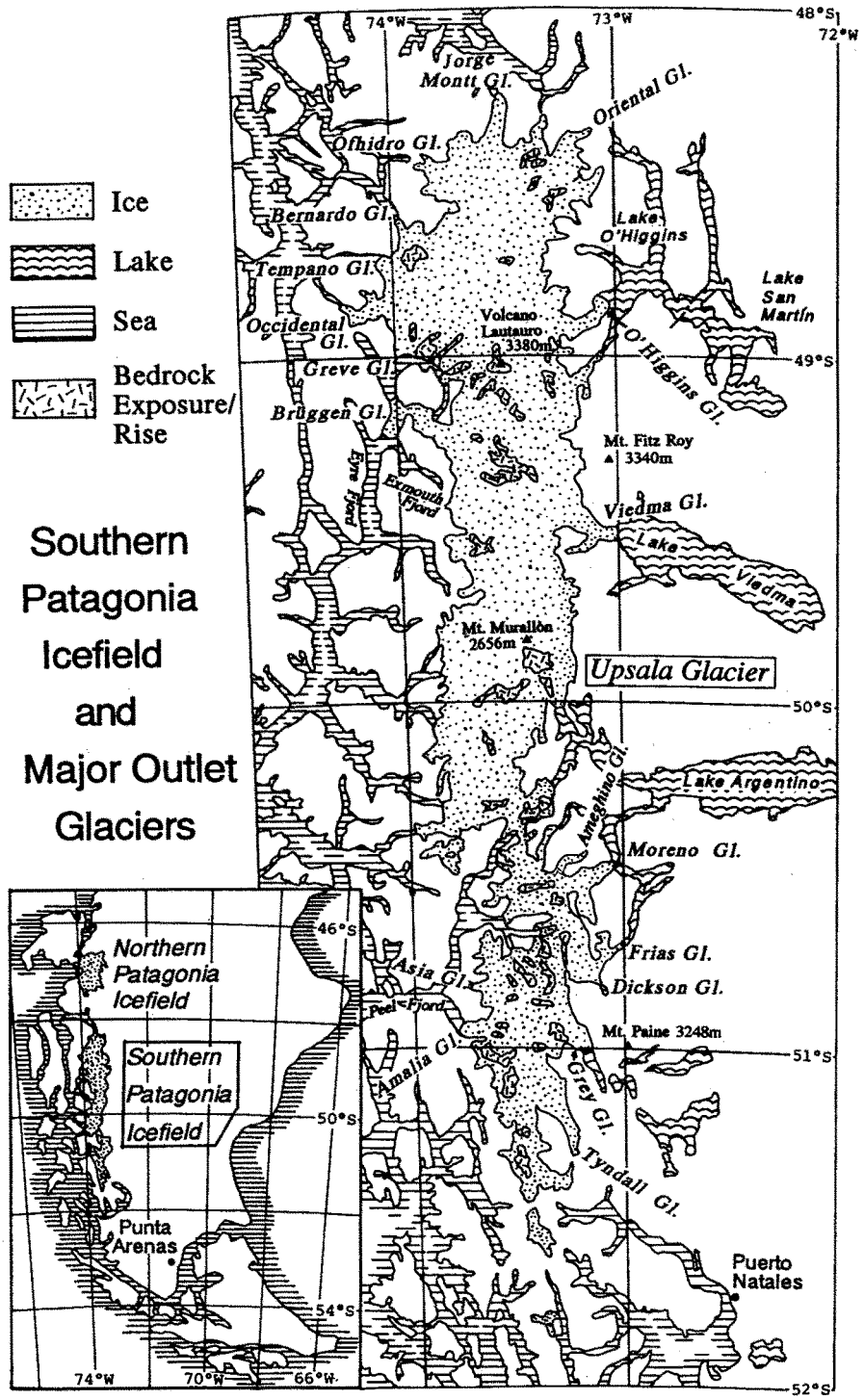

Fig. 1. Southern Patagonia Icefield and location of Upsala Glacier. Map modified after Lliboutry (1956). Elevations of Co. Murallón and Co. Paine Grande are taken from topographic maps published by Argentinean and Chilean governments, respectively.

tions. It is the purpose of this study, on the basis of these new findings, to propose a new scheme of Neoglacial advances in the Upsala Glacier area.

2. Study Area

Upsala Glacier is one of the largest glaciers in South America, with an area of 870 km² and a length of 60 km (Aniya and Skvarca, 1992). It flows southward from the icefield, with its main body terminating currently in Brazo Upsala of Lago Argentino, at an elevation of 175 m (measured with a geodetic GPS, Trimble 4000SSE, Leiva, Per. Comm.) around 49°59′S and 73°17′W (Fig. 2).

The width of the glacier body drastically changes about 7 km upstream of the current snout, from about 3 km wide to more than 7 km wide. A high ridge runs north-south at the western edge of Peninsula Herminita, and for the lowest 7 km, only the western side of this high ridge is currently occupied by the glacier, while the eastern side has become a dry valley, with a proglacial lake, Lago Guillermo, in front of the current snout of the eastern body. The Peninsula Herminita stretches south of this dry valley, separating Brazo Upsala to the west and Bahia Cristina (or Brazo Norte) to the east.

Bedrocks are mostly mudstone, often with sandstone and shale interbedded. The northern half of the Peninsula is extensively covered by fresh till (dark area in Fig. 2). The middle part is characterized by rows of moraines and extensive outwash plains. The southern part is massive bedrock hills, generally covered with thin till and sparse vegetation.

3. Moraines

There are three major moraine systems around Upsala Glacier that indicate major Neoglacial advances. They are, from older to newer, Herminita moraines, Pearson I moraines and Pearson II moraines (Fig. 3). Although there are moraines on the west flank of Co. Feruglio and around the Lago Pearson (or Anita, see Fig. 2), description is restricted to those on the Herminita Peninsula.

3.1. Herminita Moraines

Near the southern end of the Peninsula Herminita, fields of moraines are spread out, representing a major Neoglacial advance of Upsala Glacier. On the west side of the Peninsula these terminal moraines run almost N-S, while on the east side they run about E-W. These moraines were first identified by Malagnino and Strelin (1992) and named Herminita moraines. This is the oldest moraine recognized on the Peninsula. From their running directions and characteristics given below, it is certain that the western part was laid down by the main body of Upsala Glacier that advanced along the present Brazo Upsala, while the eastern part was deposited by the eastern body that advanced along the present Bahia Cristina.

Herminita moraines West has several well-defined moraine ridges, consisting largely of dark, plutonic/metamorphic rocks. There is one sharply defined, continuous moraine ridge, which probably indicates a major still-standing period (Fig. 4). Erratics scattered on and around these moraines are often gigantic. Angular erratics with diameter exceeding 5 m are not rare in this moraine field (Fig. 5). They are quite angular, with no trace of edge rounding at all. Therefore, most materials constituting the Herminita moraines West were transported probably supraglacially or englacially without influence of running water.

Herminita moraines East has no definite, continuous ridges. The moraine field is widely covered by scattering huge erratics (Fig. 6) whose diameter exceeding 4–5 m are not rare, like those on the west side. However, the lithology of these erratics is totally different from the western counterpart : being mostly slightly metamorphosed mudstone and slate. Among these scattered huge boulders are numerous, isolated moraine mounds. As the field goes east, moraine mounds become less obvious and near the shore of Bahia Cristina there are only piles or heaps of boulders and scattered erratics, without any definite moraine mounds.

Vegetation is distinctively different between the north and south of the Herminita moraines ; the south with fairly densely-populated large Nothofagus (DBH, 50–60 cm) while the north mostly with only grasses which are sporadically spotted with a few Calafate. The eastern part has more vegetation than the western part, suggesting that the eastern part had been released from the ice-cover earlier than the western part. On the south, depressions, which ponds once occupied, have been filled up with sediments and many of them have become boggy, whereas on the north most ponds are still full of clear water with little sedimentation.

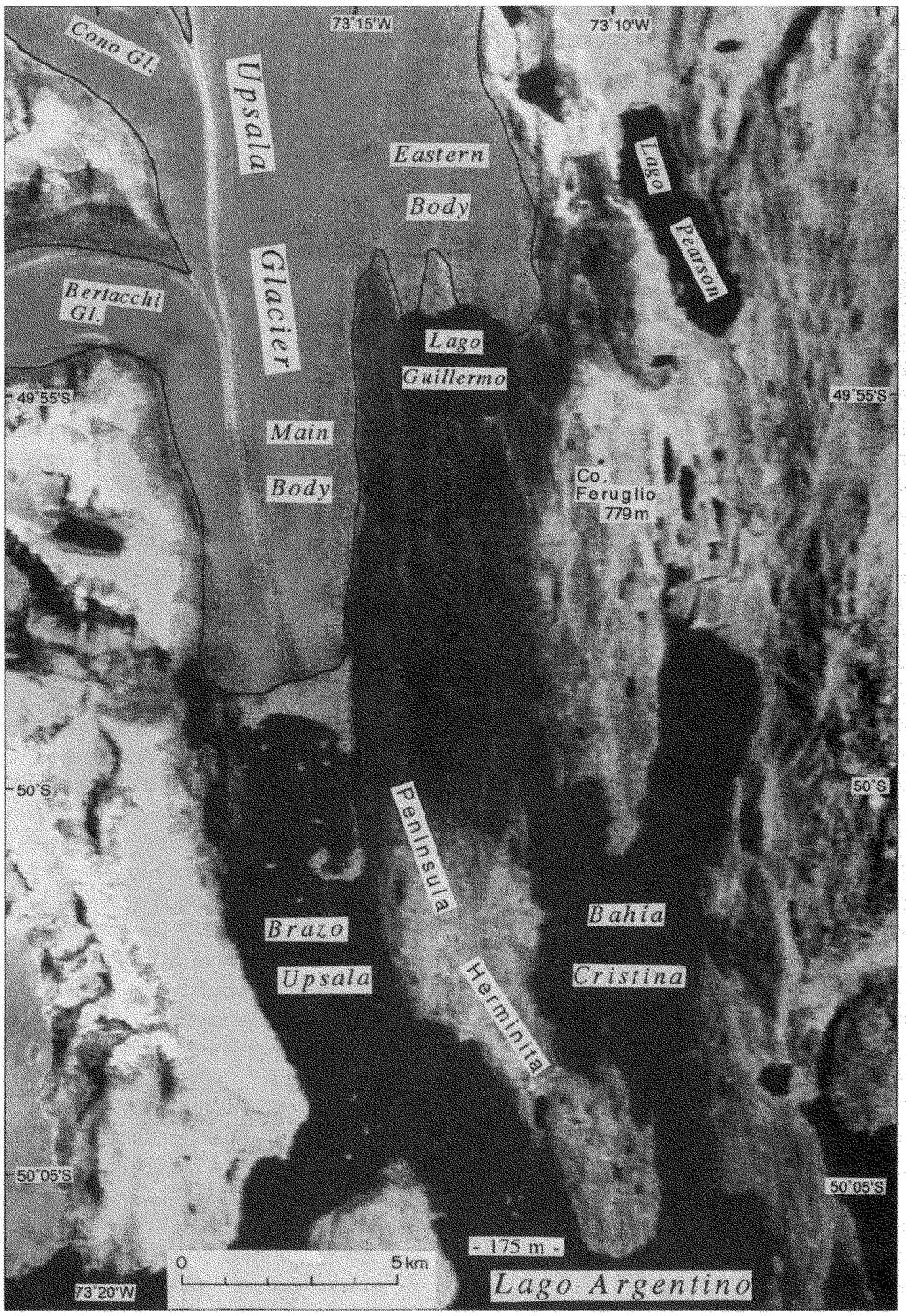

Fig. 2. Landsat TM image (January 14, 1986) showing Upsala Glacier and Peninsula Herminita. Original image was produced using band 1 (0.45−0.52 μm), 4 (0.76−0.90 μm) and 5 (1.55−1.75 μm). The darkness of the northern half of the Peninsula Herminita indicates that the vegetation is devoid or sparse implying the recent deglaciation.

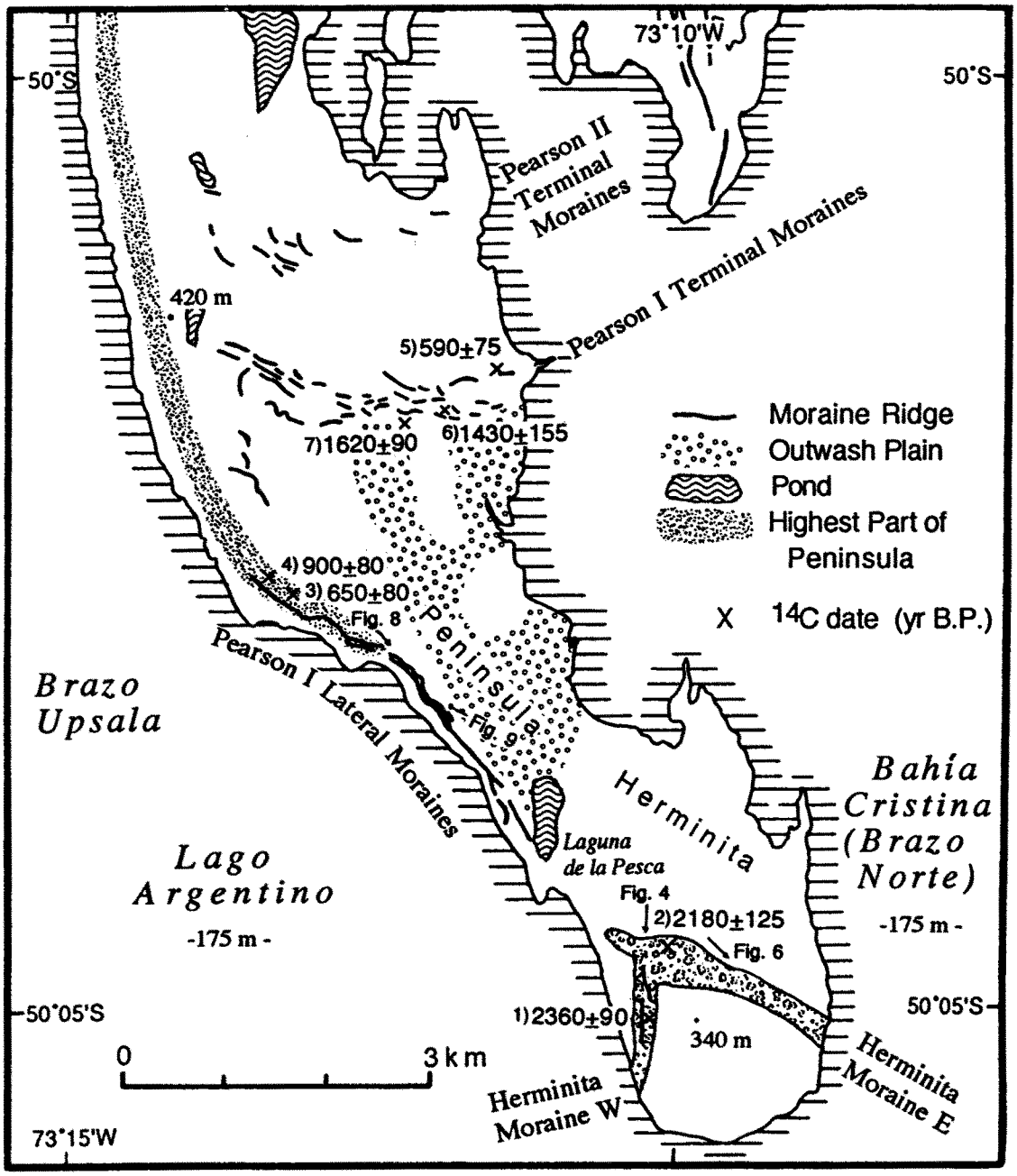

Fig. 3. Detailed map of moraine distributions and ^{14}C datings at the southern half of Herminita Peninsula. The outline of land is direct tracing on the 1981 aerial photograph. Photographic poins of Figures 4, 6, 8 and 9 are indicated.

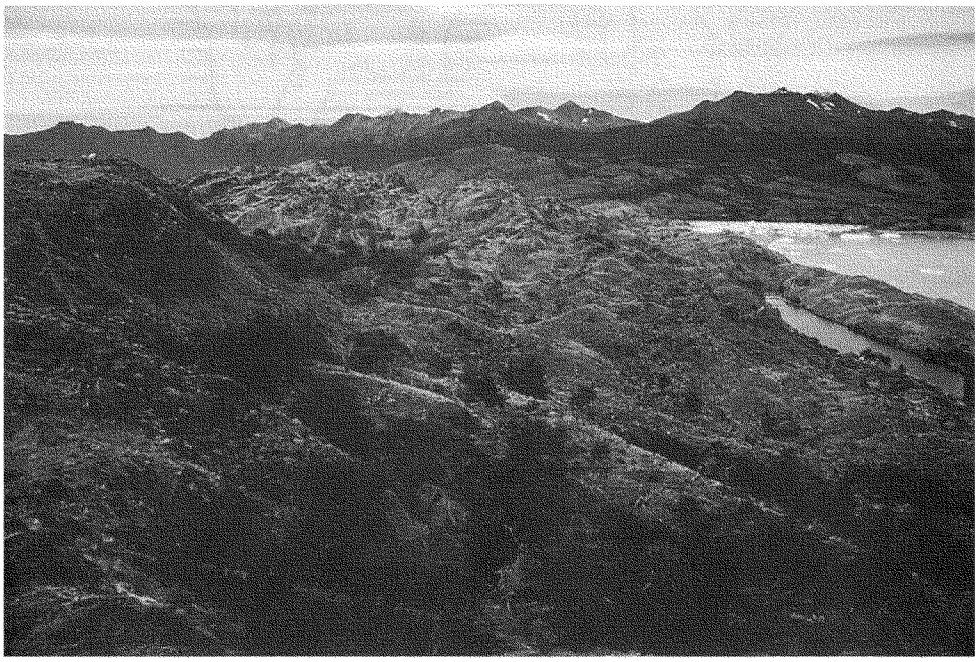

Fig. 4. Herminita Moraines West. Looking southward. Sinuous moraine crests and mounds in the middle, and large erratics scattered around are visible.

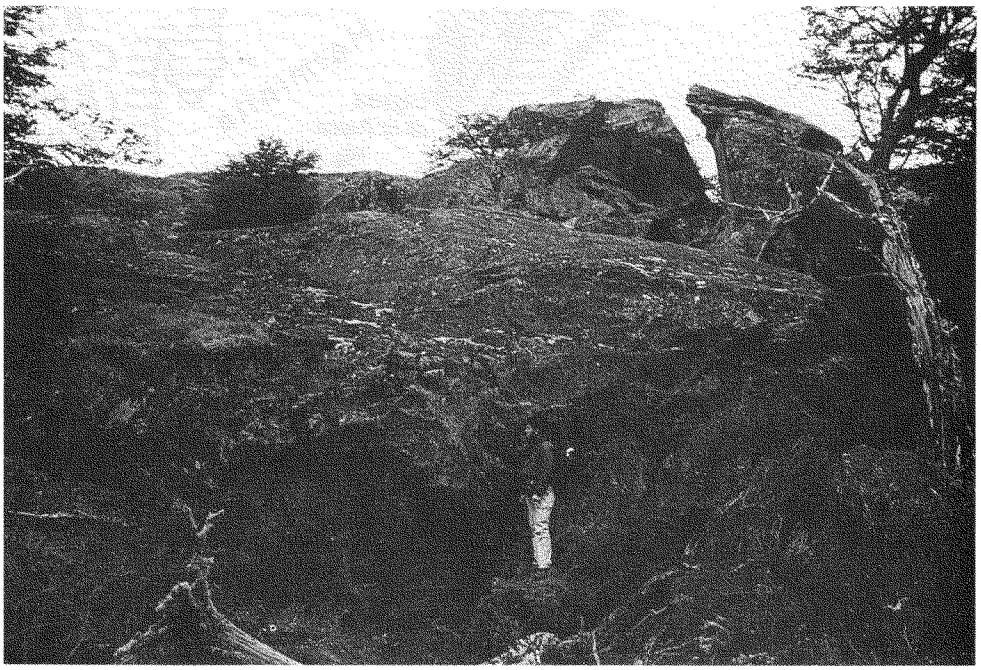

Fig. 5. Gigantic erratics at Herminita Moraines. They are invariably angular.

Fig. 6. Herminita Moraines East. No definte ridges. A fuzzy belt indicating piles of huge erratics runs in the middle of the picture, almost vertically with slight tilt to the left.

3.2. Pearson I Moraines

The Pearson I terminal moraines run across near the middle of the Peninsula, with a few rows of moraines (Fig. 7) ; but three distinctive rows can generally be recognized. These rows are separated by a small outwash plain and/or a depression with/without (dried) a pond. They are referred here to as the Pearson Ia, Ib, and Ic from the older to the newer. The Pearson I terminal moraines were formed by the eastern body of Upsala Glacier. Their reliefs in general range from about 10 m to 20 m.

The Pearson I lateral moraines are very conspicuous along the western edge of the Peninsula Herminita, standing above the extensive outwash plain to the east (Fig. 8). They stand up about 15 to 40 m higher from the adjacent outwash plain and are mostly composed of round gravel and boulders. One of the characteristics is that moraines are mostly double-ridged, often with broad depressions between the ridges (Fig. 9 foreground). These moraines were formed by the main body of the glacier, and are what Shaw (1980) termed Röthlisberger-Schneebeli moraine. Shaw (1980) explained the formation of Röthlisberger-Schneebeli moraine by a secondary (lateral and upward) flow of the glacier and called them "half fluting". Round gravels were brought up to the surface by a secondary flow generated by longitudinal folding of the glacier due to convergent flow. The double ridges formed with this mechanism can probably be interpreted to represent two different glacial advances of the similar magnitudes.

3.3. Pearson II Moraines

The Pearson II terminal moraines are located about 0.9−1.4 km behind the Pearson I terminal moraines. The Pearson II and I moraines are separated by a broad belt of outwash plains, glacio-fluvial channels, and terraces, which is characterized by relatively high reliefs due to bedrock irregularity and vegetation along channels and marshes. This is quite a contrast to the area south of the Pearson I moraines, where the extensive outwash has buried the bedrock relief, making the surface very flat and mostly devoid of vegetation. Ponds occupying depressions among the Pearson II moraines are still fresh, with clear water and no/little sedimentation of dead plants on the bottom.

Fig. 7. Pearson I terminal moaines. Right is Pearson Ia and left is Pearson Ib. Outwash plains are located between these moraines. Looking eastward from near the western edge of the moraine field.

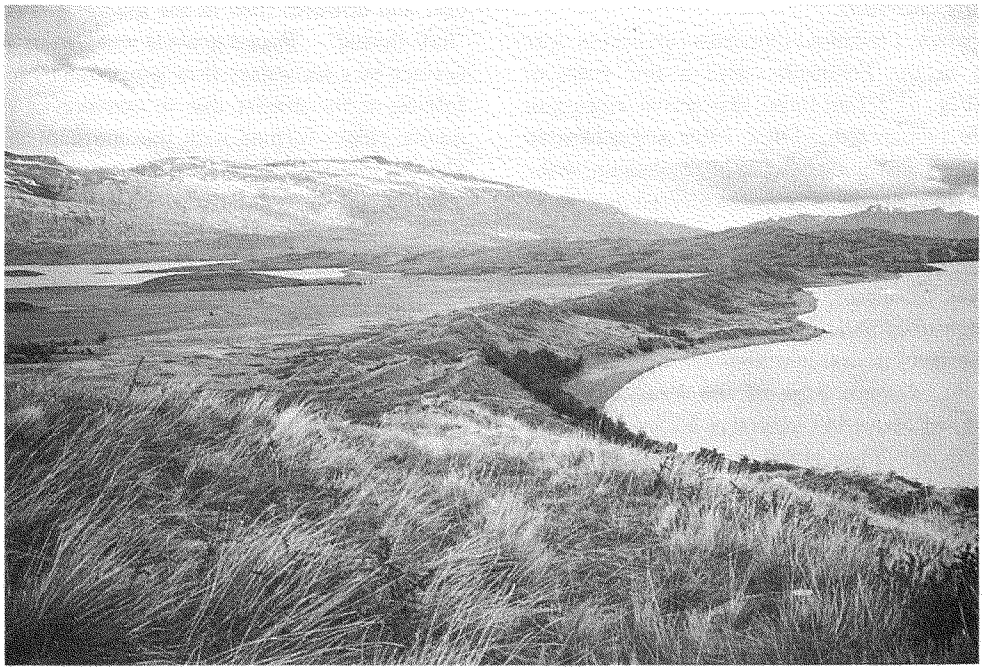

Fig. 8. Pearson I lateral moraines. Looking southeastward. The moraine ridges are on the shore of Brazo Upsala. Extensive outwash plain on the left side. Far back : bedrock hill where Herminita moraines are located

Fig. 9. The double ridges of Pearson I lateral moraine. Looking northward. Gravel and boulders are mostly round/subrounded. This is what Shaw (1980) called "half-fluting".

4. Holocene Glacial Chronology

We collected peat samples from dry or semi-dry ponds located between a terminal moraine and the bedrock hillslope or among moraine ridges for ^{14}C dating, with which to elucidate a glacial chronology of the Upsala Glacier area (see Fig. 3). The problems associated with the interpretation of a ^{14}C date in relation to the date of the actual glaciation were discussed by Mercer (1970, p. 6). Since we cannot estimate how long it took for each of the peat samples to develop, and a ^{14}C date is listed with plus and minus to indicate the error margins, a particular date correction was not applied to each data. Descriptions of theses samples are summarized in Table 1.

At the Herminita moraines two peat samples were collected. A peat sample (NU-629) collected at the Herminita moraine West is dated to be 2360 ± 90 yr B.P. At the Herminita moraine East, another peat sample (NU-630) collected from a dry pond located among moraine mounds yielded a date of 2180 ± 125 yr B.P. The first sample was recovered from a semi-dry pond that was formed after a Neoglacial advance maximum, while the second one indicates a substage of the Herminita glacial advance. Consequently, these two dates appear compatible to each other.

Around the Pearson I moraines, five peat samples were collected from dry or semi-dry ponds. A sample (NU-635) was collected from a dry pond located between the Pearson Ia terminal moraine and the gentle bedrock hillsope. The sampled pond lies about 50 m in front of the Pearson Ia with an outwash plain between them, and below the peat is a layer of brown soil (silt) 2 cm thick resting on top of fine sand. The sample yielded a date of 1620 ± 90 yr B.P. Because of the sample location and soil development underneath, the interpretation of this date may be amgbiguous. The pond may have been formed by outwash coming from the advancing glacier (not yet reached the maximum extent), or by outwash after forming the Pearson Ia (reached the maximum). However, it is certain that this date is related to the readvancing glacier after the Herminita glaciation. From a semi-dry pond located between the Pearson Ia and Ib moraines, a sample (NU-634) was recovered, that indicated the date of a substage during the Pearson I advance. It is 1430 ± 155 yr B.P. These two samples indicate that there were Neoglacial advances at *ca.*

Table 1. Description and Dating of Samples at Peninsula Herminita

1) NU-629 (Peat)
^{14}C dating : 2360±90 BP or *ca.* BC 410
Site : Herminita Moraine, West. Elevation 257 m. Bog formed between the terminal moraine and the hillslope.
Stratigraphy : Peat thickness unknown due to rapid water seepage. 40 cm from the surface. Below : sand. Top : dark soil, 40 cm.
Significance : Indicates the minimum age of Herminita Glaciation.

2) NU-630 (Peat)
^{14}C dating : 2180±125 BP or *ca.* BC 230
Site : Herminita Moraine, East. Elevation 297 m. Depression among moraine mounds.
Stratigraphy : Peat 5 mm thick. 22 cm from the surface. Below : clayee soil, 6 cm thick. Then : sand and angular gravel. Top : clayee soil, 12 cm thick. Then : humus, 10 cm thick
Significance : Indicates a substage of Herminita Glaciation.

3) NU-631 (Peat)
^{14}C dating : 650±80 BP or *ca.* AD 1300
Site : Pearson I Lateral Moraine. Elevation. 260 m. Depression formed between Pearson I Lateral Moraine and the bedrock (gentle hillslope).
Stratigraphy : Peat 5 mm thick. 12 cm from the surface. Below : soil, 5 mm thick. Then : sand. Top : dark soil, 12 cm thick.
Significance : supposed to indicates the age of Pearson I Glaciation, but the date may be younger than the surface because of soil development underneath.

4) NU-632 (Peat)
14C dating : 900±80 BP or *ca.* AD 1050
Site : Pearson I Lateral Moraine. Elevation 275 m. Depression among lateral moraines.
Stratigraphy : Peat 2 cm thick. 12 cm from the surface. Below : silt and clay with gravel mixed, 3−4 cm thick. Top : dark soil.
Significance : Indicates a substage of Pearson I Glaciation

5) NU-633 (Peat)
^{14}C dating : 590±75 BP or *ca.* AD 1360
Site : Pearson Ic Terminal Moraine. Elevation. 205 m. Peripheral of a semi-dry pond behind (glacier side) Pearson Ic moraine.
Stratigraphy : Peat 1 cm thick. 15 cm from the surface. Below : sand and silt, 7 cm thick, Then : silt and clay. Top : brown soil, 1 cm thick. Then : dark soil, 14 cm thick.
Significance : supposed to indicates the lower limit age of Pearson Ic, but the date may be much younger than the surface because of sand and silt layer 7 cm thick underneath which rests on top of silt and clay sediments.

6) NU-634 (Peat)
^{14}C dating : 1430±155 BP or *ca.* AD 520
Site : Pearson Ia. Elevation. 210 m. Peripheral of a bog which was formed just behind (glacier side) Pearson Ia.
Stratigraphy : Peat 5 mm thick, 15−17 cm from the surface. Below : silt. Top : brown soil (silt), 5 cm thick. Then : dark soil (silt), 10 cm thick.
Significance : Indicate the age of Pearson Ib Terminal Moraine (substage of Pearson I).

7) NU-635 (Peat)
^{14}C dating : 1620±90 BP or *ca.* AD 630
Site : Pearson Ia Terminal Moraine. Elevation. 215 m. Depression formed between outwash surface 50 m away from a Pearson Ia Terminal Moraine and bedrock, in front of the moraine.
Stratigraphy : Peat 1 cm thick. 13 cm from the surface. Below : brown soil (silt), 2 cm thick. Then : find sand. Top : brown soil (silt), 8 cm thick. Then : dark soil (silt and clay), 5 cm thick.
Significance : Indicate the approximate age of Pearson Moraine Ia?.

1600−1400 yr B.P. This date is close to the third Neoglacial advance which Clapperton and Sugden (1988) proposed. A sample (NU-633) was collected from a semi-dry pond, that was probably formed during the retreat from the Pearson Ic, with a date of 590±75 yr B.P. or *ca.* A.D. 1360. There is a time gap of some 1000 years between this date and above two dates. Since below the peat sample there is a layer of sand and silt 7 cm thick resting on top of silt and clay sediments, the formation of the peat may not closely indicate the date when the glacier started receding from the Pearson Ic moraine.

Two samples were collected at Pearson I lateral moraines near the northern end. A sample (NU-631) was collected from a dry pond located between the Pearson I lateral moraine and the bedrock hillslope. The date of this sample is 650±80 yr B.P. or *ca.* A.D. 1300. Below this peat layer there is soil of 5 mm thick. So again this date may be much younger than the date of the glacial advance that formed the pond. From a depression among the Pearson I lateral moraines slightly further north than NU-631, another peat sample (NU-632) was collected and dated to be 900±80 yr B.P. This date is about 500 years younger than the date obtained at the terminal moraine. Whether this date represents another glacial advance or indicates a substage of Pearson I such as Pearson Ic cannot be ascertained. No peat was found with which to examine the date of the Pearson II.

5. Discussion

In the Upsala Glacier area, a pioneering work of glacial geology was carried out by Mercer (1965) who had identified two major Neoglaciations, Pearson I and II. A log embedded on the right bank (lateral moraine) of Brazo Upsala is dated to be *ca.* 2300 yr B. P. (Fig. 10). He did not obtain samples from the Pearson I terminal moraines on the Peninsula Herminita. A peat sample collected at south of Lago Pearson yielded a date of *ca.* 2000 yr B.P. From these two dates, he has assigned a date of *ca.* 2300 yr B.P. to the Pearson I advance. The Pearson II moraines represent a Little Ice Age advance and are estimated to have culminated at *ca.* A.D. 1600−1760 from dendrochronological analyses. Besides these Neoglacial advances, he dated another glacial advance at *ca.* 3600 yr B.P., from a peat sample obtained at a site near the sample site of *ca.* 2000 yr B.P. He was skeptical of this Neoglacial advance, however, simply because the proximity of the two sample sites implies that the magnitudes of the two glaciations had been very close. Recently Aniya and Sato (1995) identified a Neoglaciation that occurred at *ca.* 3600 yr B.P. (NU-640) in the Tyndall Glacier area near the southern end of the SPI, confirming the existence of a glaciation at this date.

From the results at Upsala Glacier and other glaciers, Mercer (1970, 1982) postulated a scheme of three major Neoglacial advances in Patagonia. Later, Clapperton and Sugden (1988) suggested another at 1300−1000 yr B.P., thereby proposing four major Neoglaciations ; *i.e.* 4500−4000 yr B.P., 2700−2000 yr B.P., 1300−1000 yr B.P, and the Little Ice Age. When we were collecting peat samples for dating, we postulated the Herminita moraines to be *ca.* 3600 yr B. P., since it precedes the Pearson I. However, the ^{14}C dates obtained in this study indicate quite different glacial chronology. The Herminita glacial advance occurred at *ca.* 2400−2200 yr B.P., corresponding to a second Neoglacial advance. A piece of wood found on the right bank of Brazo Upsala and dated to be *ca.* 2300 yr B.P. (Mercer, 1965) perfectly fit into the period of the Herminita advance. Since this sample site was covered during the Herminita, Pearson I and II glaciations, the correlation of the lateral moraine with terminal moraines was mixed up and the confusion of the glacial stage had occurred. On the basis of this sample, the Pearson I advance has long been believed to have occurred at *ca.* 2300 yr B.P. The dating of the Pearson I terminal moraines indicates that the Pearson I glacial advance had occurred at *ca.* 1600−1400 yr B.P., a similar period to a third Neoglacial advance. Another third Neoglacial advance has been recognized for the first time in Patagonia at Tyndall Glacier area (Aniya and Sato, 1995). It is not certain whether the date, *ca.* 900 yr B.P. (or *ca.* A.D. 1050), obtained at the Pearson I lateral moraine corresponds to a substage of the Pearson I advance (Ic), or indicates another glacial advance before the onset of the Little Ice Age advance. Since the topography and terrain condition drastically change north of the Pearson Ic moraines, the third Neoglaciation represented by the rows of the Pearson I moraines may have lasted for a long time, from *ca.* 1600 yr B.P. until *ca.* 900 yr B.P.

One big question remains unanswered in the scheme presented above. What happened to a glaciation dated *ca.* 3600 yr B.P.? There are no moraines older than the Herminita moraines on the Peninsula Herminita. If we assume that the surface gradient

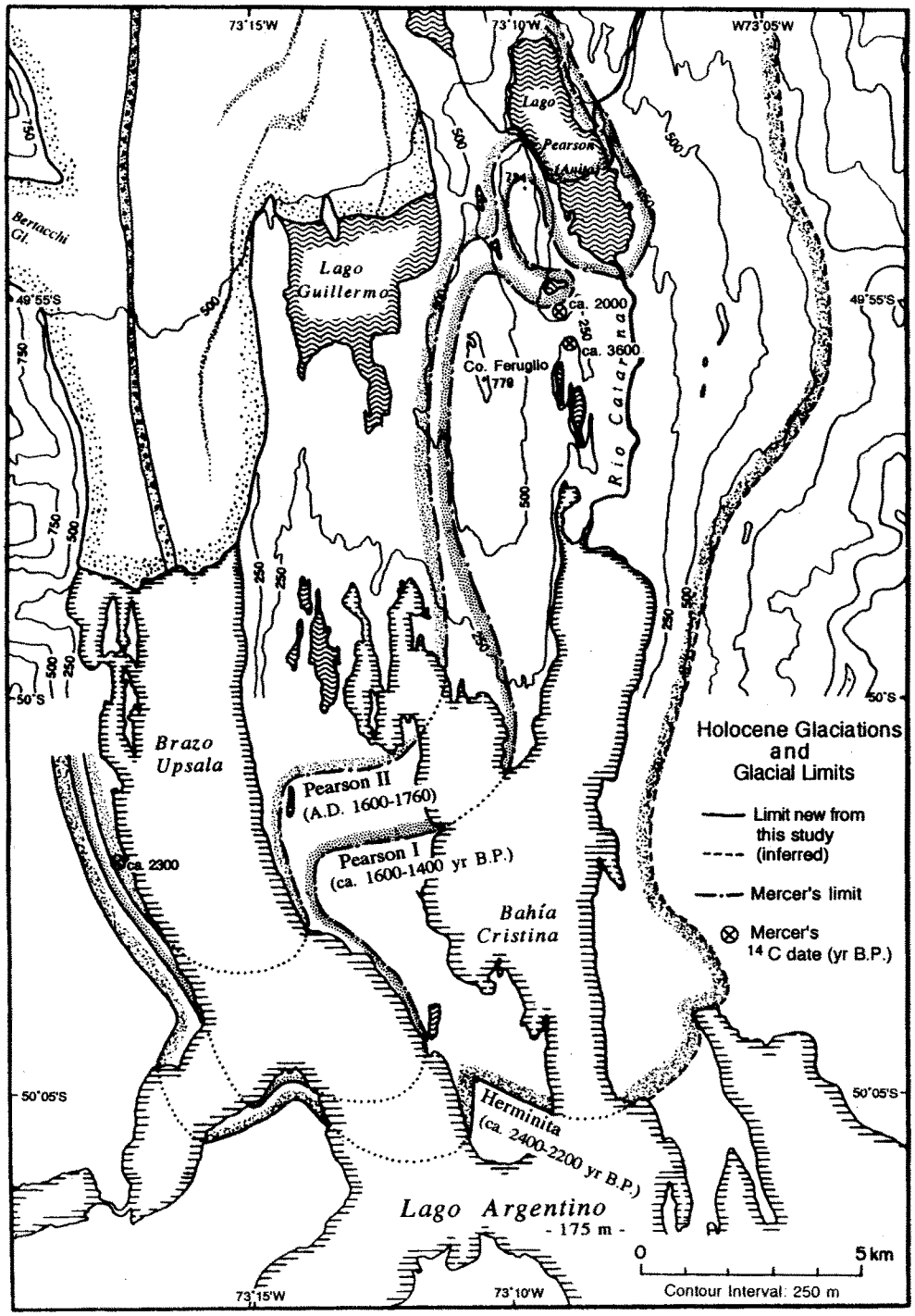

Fig. 10. A scheme of the Holocene glacial chronology of Upsala Glacier and the glacier extent at each glaciation. Top half with contours was taken from a topographic map "Glaciar Upsala" (1 : 100,000 with a 50 m contour interval) published by Instituto Geográfico Militar of Argentina, while the bottom half without contours is direct tracing on the 1981 aerial photograph.

near the glacier snout was similar during the Herminita stage to that of today, the elevation of the glacier surface near the Lago Guillermo would have been about 1000−1100 m, that would have completely covered the sites where Mercer recovered peat samples for dates of *ca.* 2000 yr B.P. and 3600 yr B.P. Since the Herminita advance caluminated at *ca.* 2400−2200 yr B.P., it can be postulated that while slowly receding the glacier formed hummocky moraines where the sample of *ca.* 2000 yr B.P. was collected. Then, how do we interpret the date *ca.* 3600 yr B.P. Although Mercer was skeptical of the glaciation at *ca.* 3600 yr B.P., it appears valid from data obtained at other glaciers. For example, at Tyndall Glacier, Aniya and Sato (1995) identified two Neoglaciations of the similar extent and the date of the older is *ca.* 3600 yr B.P., although the date of the younger could not be obtained. Other examples come from Mercer himself, who has obtained a date of 3740±110 yr B.P. at Ohfidro Sur Glacier (1970) and 3465±130 yr B.P. at Frias Glacier (1976). Only plausible interpretation seems that the glaciation at *ca.* 3600 yr B.P. was less extensive than the glaciation at *ca.* 2400−2200 yr B.P. at Upsala Glacier. It seems certain that there was a glacial advance at *ca.* 3600 yr B.P. at some glaciers in Patagonia.

From the dates discussed above and data from Mercer (1965), together with aerial photograpic interpretation of landforms and trimlines, the glacial extent of each glaciation was inferred and a scheme of Holocene glacial chronology of Upsala Glacier is summarized in Figure 10. The differences between Mercer's scheme and this study's scheme is indicated in Table 2.

6. Conclusion

A new scheme of the Neoglacial advances for Upsala Glacier was presented on the basis of the several new ^{14}C dates at the Peninsula Herminita, in which four Neoglaciations were recognized and the age assignment of the Pearson I moraines changed. As for a first Neoglaciation which is supposed to have occurred at *ca.* 3600 yr B.P., its existence cannot be directly confirmed by landforms, because its extent was less than the second glaciation. However, the ^{14}C data from other areas strongly suggest that there could have been such an advance at Upsala Glacier too. A second Neoglaciation, represented by the Herminita moraines, the oldest directly recognizable ones in this area, are dated to be *ca.* 2400−2200 yr B.P. This date agrees well with other glaciers in Patagonia. A third Neoglaciation, the Pearson I glacial advance, had occurred at least *ca.* 1600−1400 yr B.P., roughly corresponding to a third Neoglacial advance proposed for the Andes ; however, since there is another date, *ca.* 900 yr B.P., for the Pearson I lateral moraine, the Pearson I advance may have lasted very long, close to 700 years, until 900 yr B.P. or *ca.* A.D. 1050. A fourth Neoglaciation, the Pearson II, had occurred during the Little Ice Age, between A.D. 1600−1760, as studied before.

Acknowledgments

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Table 2. Comparison of the schemes established by Mercer and this study

	Neoglaciation I *ca.* 3600 B.P.	Neoglaciation II	Neoglaciation III	Neoglaciation IV A.D. 1600−1760
Mercer	skeptical	Pearson I (ca. 2300 B.P.)	———	Pearson II
This study	yes	Herminita (ca. 2400−2200 B.P.)	Pearson I (ca. 1600−1400 B.P.)	Pearson II

ing was done by Dr. Kunio Omoto of Nihon University (Sample code NU-629, -630, -631 -632, -633, -634, -635, and -640).

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