

American Journal of Science

JUNE 1970

VARIATIONS OF SOME PATAGONIAN GLACIERS SINCE THE LATE-GLACIAL: II*

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ABSTRACT. In Chilean Patagonia, the ice on the east side of the cordillera receded into the mountains before 12,500 B.P. after an undated final Late-Glacial readvance. On the west coast, by 11,000 B.P., glaciers were smaller than they are today, implying the start of the Hypsithermal Interval. Three post-Hypsithermal Neoglacial readvances culminated before 4200 B.P., between 2700 and 2200 B.P., and in the late 18th century A.D. Between readvances, glaciers receded to within their present borders.

INTRODUCTION

The southern ice field of Patagonia extends along the Andean cordillera from lat 48° 20' S to 51° 30' S (fig. 1). Outlet glaciers, many with calving fronts, flow west toward the fiords of the Pacific coast in Chile and east toward piedmont lakes in both Chile and Argentina. Further south between lat 51° 30' S and the Estrecho de Magallanes the ice cover is fragmented, and three narrow tidewater channels extend through the cordillera, leading to Golfo Almirante Montt, Seno Skyring, and Seno Otway on the east side. Apart from their connections to the sea, these water bodies are similar in setting to the freshwater piedmont lakes further north.

In the southern summer 1967-1968 field studies were carried out in Chilean Patagonia to determine the fluctuations of the ice margins during final Late-Glacial and Postglacial times; this was a continuation of similar studies in Argentine Patagonia in 1963 and 1967 (Mercer, 1965, 1968).

The final episode of the Patagonian Late-Glacial is defined as the inferred regional readvance typified by the last expansion of piedmont glaciers on the east side of the mountains during the Punta Bandera Stade (see Mercer, 1968, p. 95). Postglacial time began as the ice started to recede from the Punta Bandera moraines. Neoglacial advances are defined, following Sharp (1960, p. 321), as those that occurred after the Hypsithermal Interval, during which the ice receded within its present borders.

On the west side of the ice field, the five northernmost outlet glaciers, terminating between lat 48° 25' S and lat 48° 50' S and with drainage into fiords tributary to the Canal Messier, were investigated (fig. 2).

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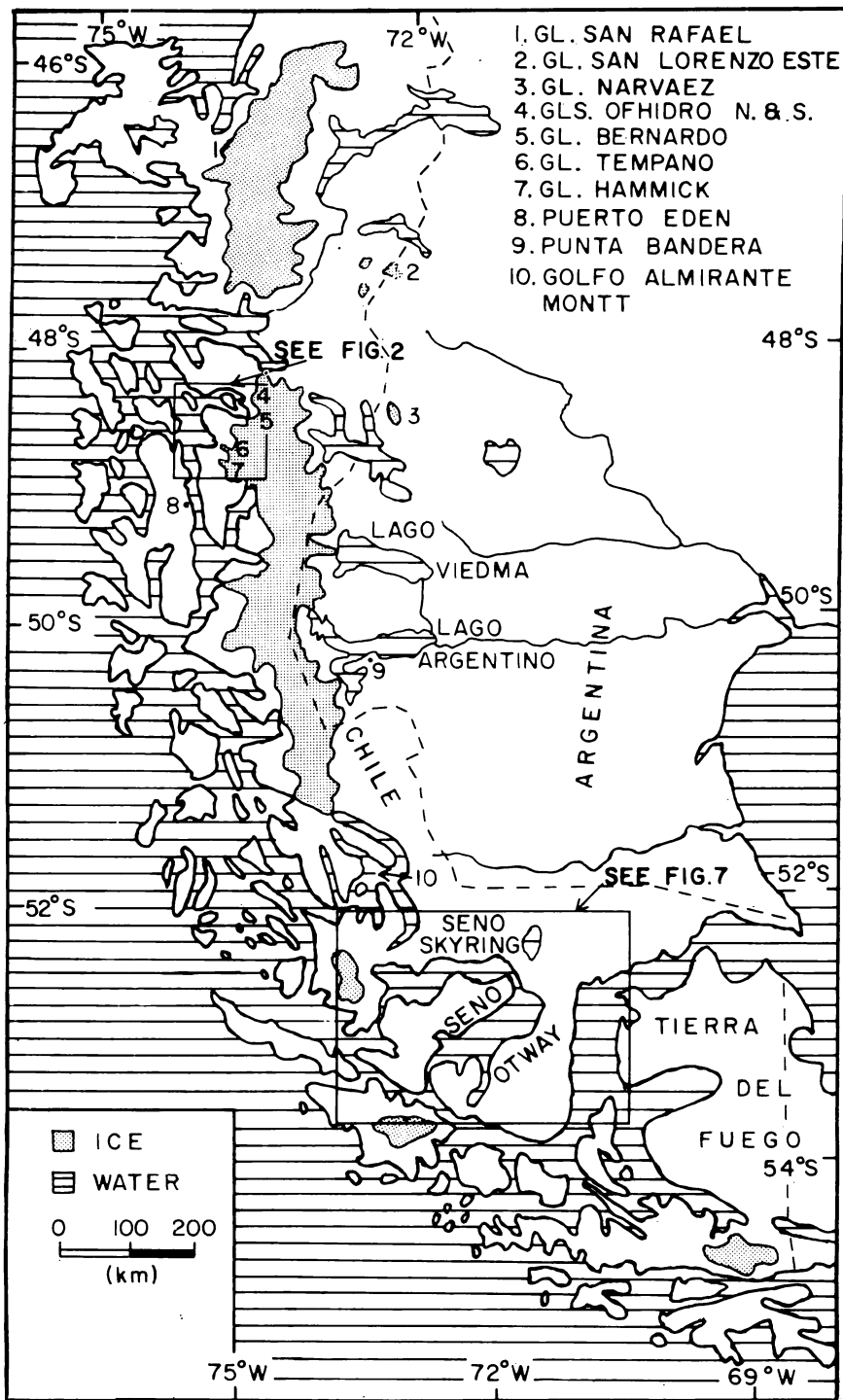


Fig. 1. The northern and southern Patagonian ice fields and their vicinity.

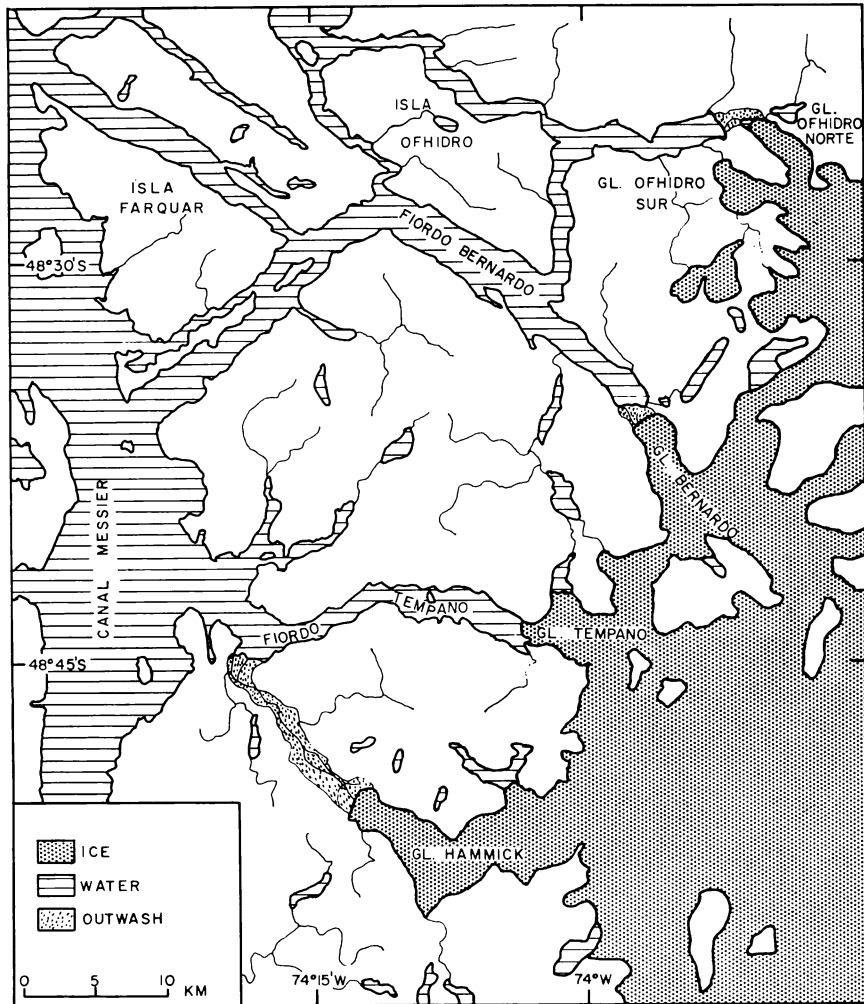


Fig. 2. Northwest outlet glaciers of the southern Patagonian ice field.

From north to south these were: Ofhidro Norte, Ofhidro Sur, Bernardo, Tempano, and Hammick.¹ In addition, an end moraine near Puerto Eden on Isla Wellington (fig. 1) was examined. On the east side of the mountains, parts of Seno Skyring and Seno Otway were studied.

The climate on the west side of the southern Patagonian ice field is extremely maritime, with heavy rainfall evenly distributed throughout the year and a small annual temperature range. In the area of study, the environment is similar to that in Fiordland, New Zealand, but temperatures are lower because of the 3° difference in latitude. Conditions are similar in many ways to those in southeast Alaska, but winters are

¹Names approved by the Instituto Geográfico Militar, Santiago.

TABLE 1

Radiocarbon dates, 1967-1968 fieldwork

Sample no.	Age: years B.P.	
I-3502	(3110 ± 130)	Basal peat from 1.5 m depth on outwash in front of first (outermost) end moraine, Glaciar Hammick. Gives minimal age for moraine but apparently not a close minimal age; see sample I-3506.
I-3503	(2300 ± 110)	Basal peat from 1 m depth on outwash in front of second end moraine, Glaciar Hammick. Gives minimal age for moraine.
I-3504	(2070 ± 95)	Basal peat from 1.3 m depth on outwash in front of third end moraine, Glaciar Hammick. Gives minimal age for moraine.
I-3505	(1545 ± 100)	Moss on cobbles covered by 25 cm sand and 1 m peat, 1500 m in front of outermost moraine, Glaciar Hammick. Dates stabilization of outwash at this site. Expected to give close minimal date for recession of ice from outermost moraine, but young age indicates outwash was active until after recession from third moraine.
I-3506	(2800 ± 100)	Wood from outer part of rooted stump 1 m in diameter exhumed from drift 50 m from present ice margin. Tree grew for about 300 yrs. Indicates that site was ice-free 3200 ± 100 B.P. and advance was in progress 2800 ± 100 B.P.
I-3507	(11,070 ± 160)	Basal peat from 60 cm depth on till, 10 m from 1968 margin of Glaciar Tempano. Site was ice-covered a few years ago, and peat is highly compressed. Gives latest date for recession of Glaciar Tempano to within its present margins; see sample I-3825.
I-3508	(4120 ± 105)	Basal peat from 1.1 m depth covering sediments of former ice-marginal lake, upper margin of Glaciar Tempano. Lake drained after ice receded from a well-marked lateral moraine.
I-3509	(7730 ± 130)	Peat covered by lake clay and modern peat, near shore of lake formerly dammed by Glaciar Bernardo. Expected to give date of impounding, but I-3823 shows that age is misleadingly young, probably because of rootlet contamination.
I-3510	(4060 ± 110)	Basal peat from about 1 m depth, second (next to outermost) end moraine, Glaciar Ofhidro Sur. Gives minimal age for moraine.
I-3511	(3740 ± 110)	Basal peat from 1.2 m depth, sixth end moraine, Glaciar Ofhidro Sur. Gives minimal age for moraine and is consistent with I-3510.
I-3512	(12,460 ± 190)	Basal peat from 1.4 m depth on cobbles, in spillway of Otway ice lake. Gives latest date for abandonment of spillway and, therefore, deglaciation of Canal Jerónimo.
I-3513	(9670 ± 160)	Basal peat from 2.4 m depth on end moraine of former valley glacier at Puerto Eden. Gives minimal age for the moraine and probably latest date for stranding of tributary glacier as mainland ice receded from coast of Isla Wellington. Must be misleadingly young (compare, samples I-3507, I-3823, I-3825).
I-3823	(10,000 ± 160)	Basal peat from 1.3 m depth between two moraine ridges 140 m above present surface of Glaciar Bernardo. Gives minimal age for the moraines; however, because basal peat was not retrievable where the peat was thickest (2 m), this is perhaps not a close minimal age.

TABLE 1 (continued)

Sample no.	Age: years B.P.	
I-3824	(270 ± 90)	Wood from outer part of splintered, rooted stump, 100 m from present front of Glaciar Bernardo. Indicates that tree was killed between A.D. 1430 and 1740.
I-3825	(11,100 ± 170)	Basal peat, from 1.5 m depth, on fluvio-glacial material, 300 m outside 18th century moraine, 1 km from terminus of Glaciar Tempano. Gives latest date for shrinkage of glacier to almost its present size. Agrees well with sample I-3507.
I-3826	(6010 ± 120)	Basal peat from 80 cm depth on a subdued moraine ridge at 360 m elevation, Glaciar Tempano. Glacier margin is at 310 m, and a moraine ridge more than 4120 C-14 years old is at 345 m (see sample I-3508). Gives a minimal age for the moraine ridge, but probably not a close minimal age.
I-3827	(800 ± 95)	Wood from central part of a rooted stump exhumed from outwash about 700 m beyond 19th century moraines, Glaciar Ofhidro Norte. Tree lived for about 100 yrs. Indicates that tree was killed, probably by outwash during ice advance, about A.D. 1300 ± 95.

warmer, and summers are cooler and windier. No records are available from near the glaciers, but annual precipitation reaches 750 cm in the archipelago to the west (Arroyo and Solar, 1958, p. 26) and perhaps also on the higher parts of the ice field (Schwerdtfeger, 1956, p. 67). Estimated mean monthly air temperatures in the Canal Messier are 3°C to 5°C in July and 12°C in January (Arroyo and Solar, 1958, p. 115 and 145). Despite the cool summers the tree line is at about 900 m. On low ground away from the rivers and active outwash flats, thick and almost impenetrable rain forest alternates with valley bogs. The forest consists mainly of evergreen southern beech (*Nothofagus*) species. Cypress (*Pilgerodendron uvifera*) is locally important at lower elevations but is not a pioneer tree species on deglaciated ground. On the hillsides, thick forest with some areas of blanket bog predominate up to about 500 m elevation, above which the trees become more scattered and more stunted, the bogs become shallower, and areas of bare rock increase in importance. Above 900 m bare rock predominates. There is evidence from tree-ring studies that the time lag before *Nothofagus* trees germinate on deglaciated ground is about 70 yrs, much greater than, for instance, the 15 yrs suggested for conifers in Washington State (Miller, 1969, p. 51). This conclusion is supported by the imperceptible changes in tree distribution on recent moraines during the 23 yrs between 1945, when aerial photographs were taken, and 1968.

Seventeen samples were dated by radiocarbon, and the results are given in table 1. Thirteen are from basal peat, three are from rooted tree stumps, and one is from moss. The basal peat samples were all obtained by digging to the bottom of the bog and not by coring, in order to avoid contamination. In the west coast field area, because of the waterlogged state of the peat bogs, the retrieval of basal peat by this method was extremely difficult below a depth of about 1.5 m.

Basal peat gives a minimal age for a feature but not necessarily a close minimal age, because the interval between the exposure of a surface from beneath ice or water and the start of peat growth must depend on several factors, the most important of which are climate, micro-relief, and composition of the surface material. Observations on ground that has been deglaciated during the last 100 to 200 yrs suggest that, in the climate of west Patagonia, the interval does not exceed a century at a badly-drained site such as the bottom of a depression among moraine ridges. At better-drained sites, however, such as outwash flats, the basal peat may be many centuries younger than the surface it covers. Another cause of misleadingly young ages for basal peat is contamination by rootlets. Living rootlets are recognizable and can be removed, but rootlets that are long dead, yet younger than the material that they penetrate, present a more intractable problem. Thus, although basal, non-limnic peat cannot be misleadingly old, it can be misleadingly young. Therefore, if two or more basal peat samples give substantially different minimal ages for the same event, the younger ages may be ignored.

RECESSION FROM THE FINAL LATE-GLACIAL SUBSTAGE ON THE WEST COAST

The type locality for the final Late-Glacial substage in Patagonia is on the east side of the mountains where end moraines mark the limits of the last readvance of piedmont lobes in Lago Argentino (fig. 1) during the Punta Bandera Stade (Mercer, 1968, p. 95). No equivalent features have been recognized to the west of the southern Patagonian ice field, but they perhaps lie in the almost unexplored archipelago near the outer coast. Thus the timing of early Postglacial recession toward the present ice margins on the west coast is unknown.

Glaciar Ofhidro Norte in Postglacial time.—The Glaciar Ofhidro Norte is about 8 km long, including the upper 3 km where it is combined with the Ofhidro Sur. It ends in a proglacial lake, bounded by a massive multiple end moraine which also impounds an extramorainal lake to the east (fig. 3). Aerial photographs show that the central part of the ice front reached the base of the moraine in 1945, separating two small proglacial lakes. By 1968 the terminus had receded 0.5 to 1 km. The main stream outlet leaves the proglacial lake near its eastern end and flows between an inactive outwash plain and the steep valley side. A much smaller stream leaves the lake near its western extremity and flows through the outwash plain (fig. 3).

Near where the main river leaves the lake, a treeless but thickly vegetated moraine lies ~20 m from the lake shore. Three older moraine ridges with scattered immature trees lie 150 to 200 m beyond; field examination of sections of the largest trees on each indicated ages of about 45, 50, and 105 yrs, if growth rings are annual. Allowing 70 yrs for the establishment of tree seedlings (an estimate based on observations at the Glacier Tempano, see below), all three moraines were formed between about A.D. 1790 and 1850. Remnants of two undated older mor-

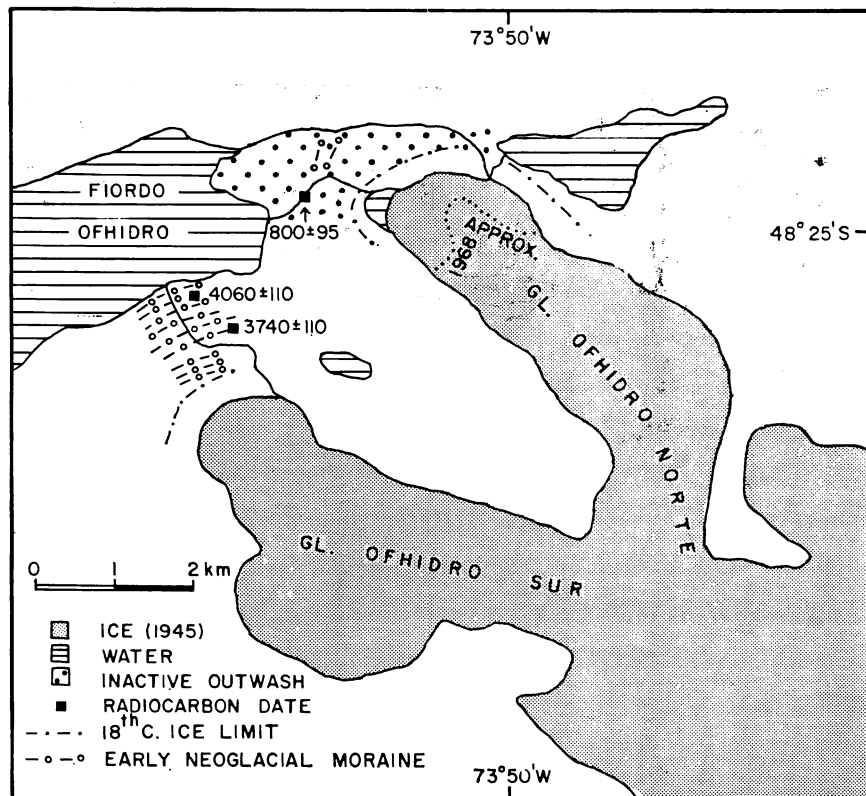


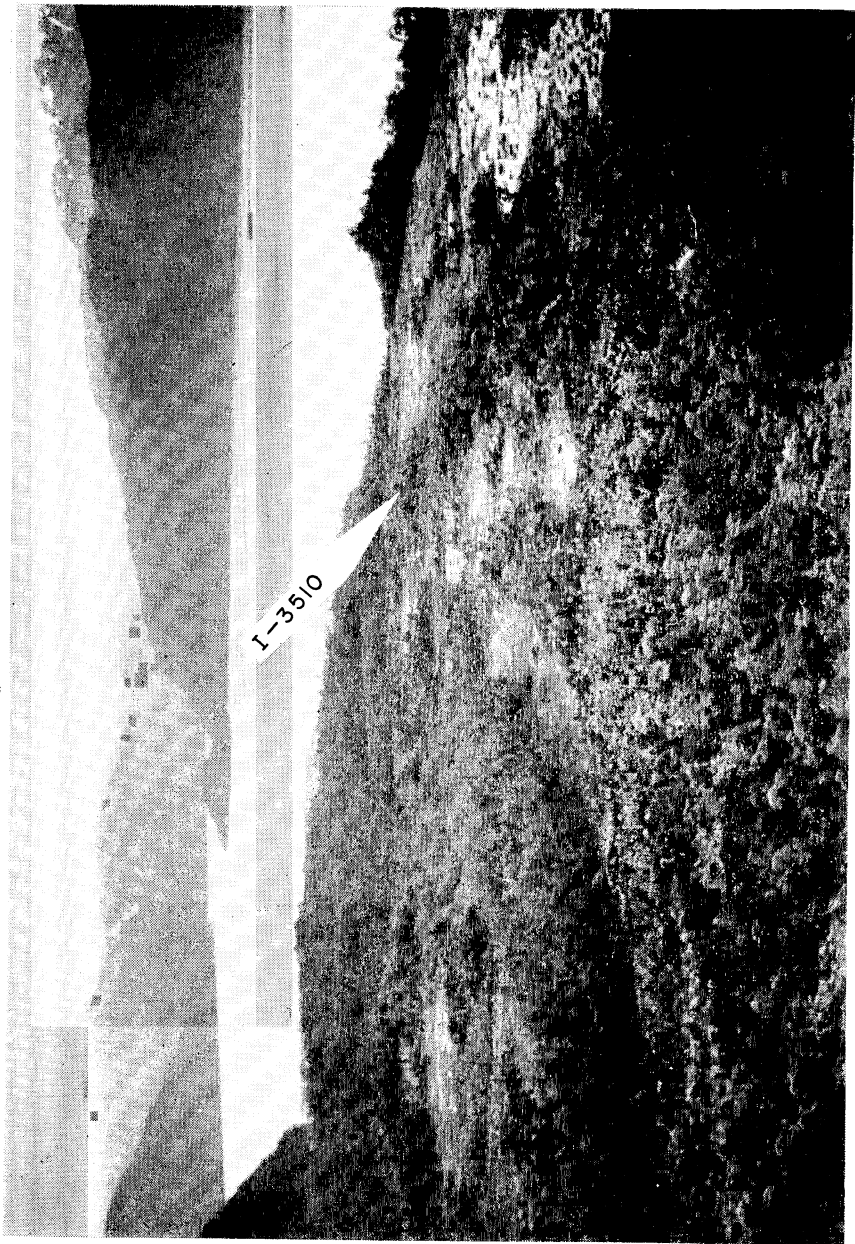
Fig. 3. Sketchmap of the glacial features near the tongues of Glaciar Ofhidro Norte and Glaciar Ofhidro Sur.

aines with mature forest cover lie about 1 km beyond the oldest recent moraines.

About 700 m beyond the late 18th century moraine, the small stream that flows from the western extremity of the lake has exhumed stumps rooted in peat 3 m below the surface of the adjacent outwash. Burial of growing trees by outwash is strong evidence that a glacier advance was in progress. The central part of a tree that lived for about 100 yrs is 800 ± 95 C-14 yrs old (I-3827); an age of 800 C-14 yrs is equivalent to about 730 calendar yrs (Stuiver and Suess, 1966), indicating that the tree died about A.D. 1300 ± 95 .

Glaciar Ofhidro Sur in Postglacial time.—The Glaciar Ofhidro Sur is about 8 km long, including the upper 3 km where it is combined with the Ofhidro Norte. The glacier ends in two lobes draining west and northwest (fig. 3); only the northwest-draining lobe was examined. The melt-stream from this lobe is entrenched in the glacial deposits and has long followed the same course, so that old end moraines are exceptionally well preserved.

PLATE I



Glacier Offhydro Sur, early Neoglacial end moraines, view west.

The glacier front and the recent moraines were not visited, but they were examined through binoculars from high ground above the east bank of the river. The ice has receded slightly from a low, unvegetated moraine ridge superposed upon the lower slope of a massive end moraine about 40 m high. This massive moraine consists of an inner vegetated but treeless ridge, lying against two ridges with a close cover of small, immature trees. An older moraine with larger but immature trees lies about 300 m downvalley. Between this oldest recent moraine and the coast 1500 m away are about nine moraine ridges 1 to 20 m high (pl. 1). Because the west side of the river was not easily accessible, studies were confined to the east side. The first, outermost moraine was too waterlogged for investigation, and basal peat samples were obtained from about 1 m depth in hollows on the second and sixth moraines; ages are 4060 ± 110 (I-3510) and 3740 ± 110 (I-3511) C-14 yrs old respectively. Three younger ridges on the west side of the river were not examined.

Glaciar Bernardo in Postglacial time.—The Glaciar Bernardo is about 22 km long. Fifteen km below where it leaves the ice field, two distributary tongues flow northeast and southwest, terminating against counter-flowing glacier fronts. The main glacier continues a further 7 km, ending close to sea level, separated from Fiordo Bernardo by a 2-km-wide outwash plain (fig. 4). The glacier now terminates 50 to 100 m from a fresh, bare end moraine (pl. 2).

About two-thirds of the outwash plain in front of the glacier is modern and is bare or sparsely vegetated, and the remainder consists

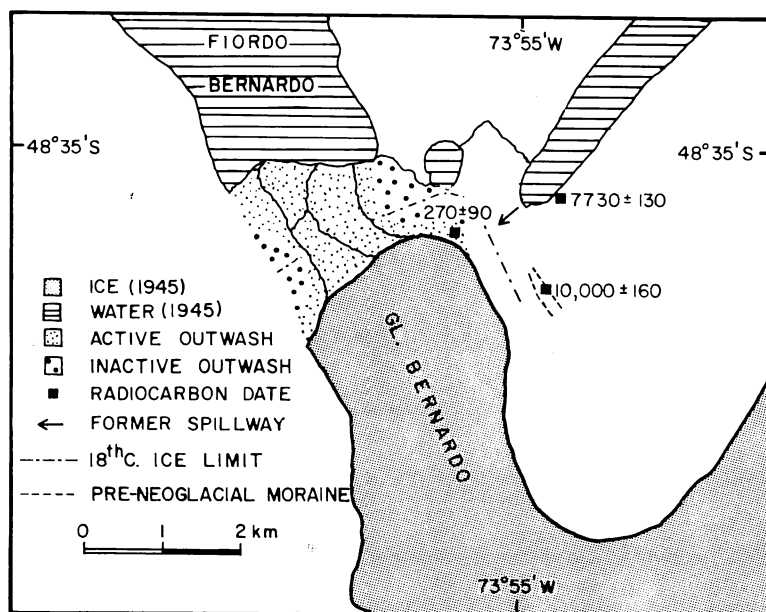


Fig. 4. Sketchmap of the glacial features near the tongue of Glaciar Bernardo.

PLATE 2



Glacier Bernardo terminus, January 1968, view northwest. Arrows show 18th century ice limit and youngest end moraine.

of fragments of an older, thickly vegetated plain with associated moraine ridges. The largest fragment of the old plain, 1500 m long, begins 300 m from the right side of the glacier terminus and extends to the fiord (pl. 2). A 100-m-wide belt of about five moraine ridges up to 4 m high crosses this plain, the outermost ridge about 600 m from the ice front. The outwash plain between the moraine belt and fiord is parkland with well-spaced trees (*Nothofagus betuloides*), none older than 125 yrs and few younger than 115 yrs (from field counts of growth rings in cores and sections). Between the trees the ground is densely covered with shrubs 1 to 2 m high, a hostile environment for seedlings which, with few exceptions, apparently became established only between about A.D. 1840 and 1850 before increasing shrub growth prevented regeneration. On the outermost moraine the largest tree cored was about 115 yrs old, but on all the other moraines trees were 75 to 85 yrs old. Thus the outwash plain became stabilized at about the same time as the ice receded from the outermost moraine. Allowing 70 yrs for establishment of seedlings, the glacier reached its greatest extent about A.D. 1775 and fluctuated near this point for 35 to 45 yrs.

One hundred meters from the present ice front, stream erosion has exhumed splintered, rooted stumps of mature trees up to 1.5 m in diameter from outwash covered by till. The age of a sample of wood from the outer part of a stump is 270 ± 90 C-14 yrs (I-3824). However, because an age of 270 C-14 yrs has three possible equivalents in calendar yrs—about 300, 380, or 430 (Stuiver and Suess, 1966)—this indicates only that the trees were overridden by the glacier probably between about A.D. 1430 and 1740.

The terminal moraines on the outwash plain continue as a belt of lateral moraines 2 to 4 m high and about 60 to 80 m above the present ice surface near the glacier terminus. The moraines are sharp-crested, with large boulders along the base of the distal faces. Several trees, tilted when the glacier was thickest, were noted along the uppermost moraine, but no living tree was found from which precise dates might have been obtained. The forest above is mature, indicating that the late 18th century advance was the greatest of recent centuries. About 120 m above the present glacier surface, 40 m above the uppermost recent moraine, are two to four closely-spaced older moraines, of similar size but more rounded in outline and with few boulders along the base of the distal faces. Peat more than 2 m thick has accumulated in many places between the ridges, and basal peat was not retrievable at these sites. A basal peat sample from a depth of 1.3 m several meters from the center of a depression between the oldest and the second moraine is $10,000 \pm 160$ C-14 yrs old (I-3823), giving a minimal age for the moraines. Because this sample might be misleadingly young, an attempt was made to obtain material giving a maximal age for the moraines at a site 1.5 km to the north, where the former outlet of a lake had been blocked by debris that was thought, because of its situation, to be part of these moraines. Lake level rose, submerging peat, and later fell as the threshold

of the new spillway was lowered. A section dug 2 m above the present lake level and 15 m from the water's edge showed 25 cm of peat on cobbles covered by 50 cm of lake clay and 30 cm of modern peat. Rootlets from the upper peat penetrated the clay to the lower peat. A sample of the upper part of the lower peat, from which as many rootlets as possible had been removed, has an age of 7730 ± 130 C-14 yrs (I-3509). This young age suggests either that the material blocking the old outflow channel is not morainal but is perhaps a rockfall—the thick forest cover made identification difficult—or that the sample was still greatly contaminated by rootlets.

Glaciar Tempano in Postglacial time.—The Glaciar Tempano is about 10 km long. It has two termini: a west-flowing tongue which reaches tidewater on a 1.5 km front and calves into the head of Fiordo Tempano (fig. 5 and pl. 3) and a north-flowing tongue which ends in a lake draining into Fiordo Bernardo. Only the calving terminus was examined.

In 1945 when aerial photographs were taken the calving front extended between two promontories marking an abrupt widening of the fiord, and the glacier margin was close to a fresh lateral moraine. By 1968, parts of the ice front had receded about 1 km and the sides of the glacier about 100 m. Three older moraines lay within 60 m of the fresh moraine; trees up to 140 yrs old grew on the outermost with mature forest beyond.

Along the forest trimline the growth ring pattern (see Lawrence, 1950) on a tilted but living cypress tree (*Pilgerodendron uvifera*) suggests that the glacier reached the outer moraine within 10 yrs of A.D.

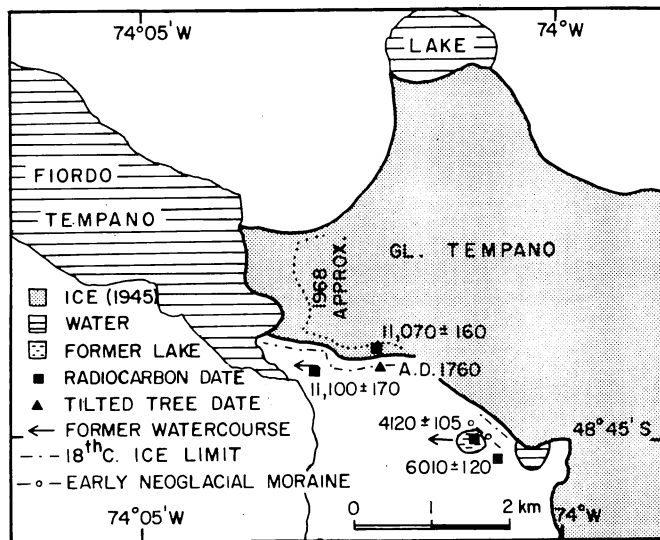


Fig. 5. Sketchmap of the glacial features near the tongue of Glaciar Tempano.

PLATE 3



Glacier Tempango terminus, January 1968, view northwest. Arrows show sites of peat samples I-3825 (left) and I-3507 (right).

1760. Thus, nearly 70 yrs may have elapsed after the glacier began to recede from the outer moraine before tree seedlings became established. This was the only ice-tilted tree from the entire field area that gave useful information; tilted *Nothofagus* trees, which were comparatively abundant, were invariably rotten in the center.

Along the lower part of the glacier the 18th century moraine marks the greatest Postglacial extent of the ice. Further up-glacier, however, an older moraine is present. About 2 km from the terminus the ice margin is now at 310 m above sea level, and the 2-m-high 18th century moraine is at 335 m. At 345 m another moraine, also about 2 m high, extends for several hundred meters along the hillside. When the glacier reached this older moraine it impounded a small lake. Peat 1 m thick now covers the lake sediments, and basal peat is 4120 ± 105 C-14 yrs old (I-3508), giving a minimal age for the draining of the lake.

About 1 km up-glacier from the ice front, a short distributary tongue protruded from the main glacier in 1945, but by 1968 it no longer existed. All the moraines formed by this tongue contain much forest debris; however, the ice was apparently slow-moving and did not erode deeply, because in many places it removed only the uppermost layers of the peat over which it advanced. Highly-compressed peat extended beneath the ice in 1968, and 10 m from the ice margin, at a point that was ice-covered a few yrs ago, 60 cm of peat rested on till (pl. 3). The basal peat is $11,070 \pm 160$ C-14 yrs old (I-3507). As a check on this surprisingly great age, two other samples were dated. At a site 300 m outside the 18th century moraine, uncompressed peat on fluvio-glacial material is exposed on the side of an abandoned meltwater channel. Basal peat from a depth of 1.5 m is $11,100 \pm 170$ C-14 yrs old (I-3825). One km further up-glacier, about 20 m above the lateral moraine with a minimal age of 4120 ± 105 C-14 yrs, are several short, subdued ridges resembling marginal features formed as the ice receded toward its present border. Basal peat from 90 cm depth between two ridges is 6010 ± 120 C-14 yrs old (I-3826). The similarity of the ages of samples I-3507 and I-3825 indicates that the Glacier Tempano had shrunk within its present margins before 11,000 B.P.; the age of sample I-3826 apparently is misleadingly young.

Glacier Hammick in Postglacial time.—The Glacier Hammick, which is about 20 km long, flows southwest from the ice field for 12 km and enters a northwest-southeast valley. A distributary tongue extends 2 km southeast into this valley, but the main tongue flows northwest, ending 12 km from Fiordo Tempano at an elevation estimated to be less than 50 m above sea level (fig. 6). Two large meltstreams issue from the right and left margins of the ice front, and a minor stream from near the midpoint. A valley train extends to the sea 12 km away.

The ice margin is now 50 to 200 m from a massive, forested end moraine 60 m high (pl. 4). Trees 150 yrs old grow on the outer face of this moraine, and trees 60 yrs old grow on a smaller moraine superposed on the inner face, suggesting that the glacier reached a maximal extent about A.D. 1750 and readvanced about A.D. 1840. Between these forested

PLATE 4



Glacier Hammick terminus, December 1967, view northeast. Arrow shows site of rooted stumps (sample I-3506), below 18th century moraine. End moraine of second Neoglacial advance is just out of picture to left.

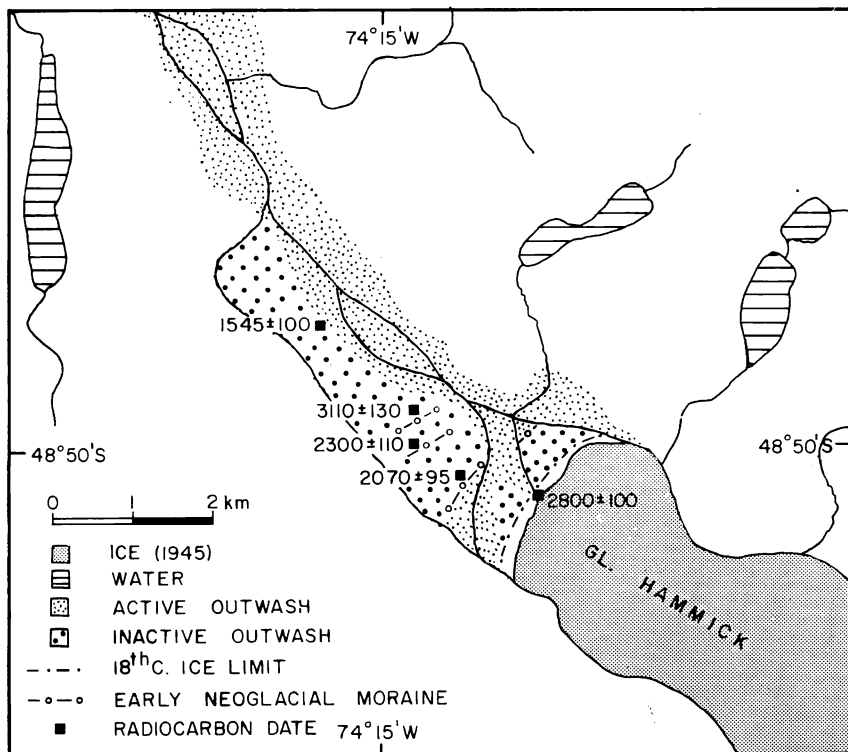


Fig. 6. Sketchmap of the glacial features near the tongue of Glaciar Hammick.

moraines and the ice are four much smaller and treeless ridges 2 to 3 m high; the two oldest are completely vegetated, the third is partially vegetated, and the fourth is bare. Aerial photographs indicate that the ice margin was in contact with or close to the youngest moraine in 1945; by 1968 it had receded 20 to 60 m from it. The distribution of trees had not noticeably changed in the 23-yr interval.

The small meltstream near the midpoint of the ice front flows through a gap in the 18th century moraine and joins the river from the right margin of the ice front about 1 km away. Near the apex of the triangle between the two is a 400-m-long fragment of an older moraine, 50 m high and with mature forest cover. Between the two moraines is inactive outwash, presumably from the recent advance, its surface 3 m above the modern rivers. The small meltstream is eroding the outwash, and many stumps, none more than 25 cm in diameter, have been exhumed; they are rooted slightly above present stream level and extend vertically for about 2 m into the outwash. No wood has been dated, but the trees were probably growing no more than a few centuries before the 18th century maximum.

Where the stream flows through the gap in the recent moraine, rooted stumps have been exhumed from 2 m of outwash covered by 60 m of overlying till. They are as much as 1.5 m in diameter and protrude 1 m above the water. Field examination suggested that these stumps were not associated with those exhumed from the outwash in front of the moraine; they were much larger and were rooted at a lower level. Wood from the outer part of a stump 1 m in diameter and which lived for an estimated 300 yrs is 2800 ± 100 C-14 yrs old (I-3506). This indicates that the outwash that killed the trees long antedates the overlying 18th century moraine.

On the left side of the valley, a 500- to 1500-m-wide remnant of an ancient valley train extends 4 km downvalley, its surface 4 to 8 m above the modern valley train. Fragments of three massive, forested moraines rise above the bog-covered outwash surface. The youngest moraine forms the upvalley margin of the old valley train and is a continuation of the 400-m-long fragment described earlier (fig. 6). Suitable peat bogs were absent on the forested moraines themselves. The ages of basal peat samples from bogs 1 to 1.5 m deep covering outwash immediately in front of each moraine were: 3110 ± 130 (I-3502), 2300 ± 110 (I-3503), and 2070 ± 95 (I-3504) C-14 yrs.

About 1.5 km in front of the outermost moraine, recent river erosion has exposed 6 m of cobbles, covered by 25 cm of river sand and 1 m of peat. The drainage pattern suggested that this part of the old valley train had become stabilized soon after the ice had receded from the outer moraine, and moss covering the uppermost cobbles was dated as a check on the age of the basal peat in front of the moraine. However, the moss is 1545 ± 100 C-14 yrs old (I-3505), indicating that the outwash became stabilized much later.

Puerto Eden end moraine.—Puerto Eden, consisting of an Indian settlement and a Chilean Air Force weather station, is situated on Isla Wellington close to the outlet of a river about 15 km long (fig. 1). A crescentic multiple end moraine about 20 m high and consisting of three closely-spaced ridges encloses the mouth of the valley and extends to the present shore at its midpoint. Fieldwork at Puerto Eden was done during a spell of exceptionally wet weather, and as a result, no basal peat could be obtained from intermorainal depressions because of water-logging. A gently sloping flat area near the crest of the central ridge was chosen for sampling. At the edge of this flat area, recent erosion had removed the uppermost 1 m of peat, leaving a further 1.4 m of peat on coarse sand. The age of the basal peat is 9670 ± 160 C-14 yrs (I-3513).

LATE-GLACIAL AND POSTGLACIAL ICE RECESSION
ON THE EAST SIDE OF THE MOUNTAINS

Ice recession in Seno Otway and Seno Skyring since Late-Glacial time.—Seno Otway and Seno Skyring are arms of the sea, although they lie east of the mountain crest (fig. 7). They are connected to the Pacific

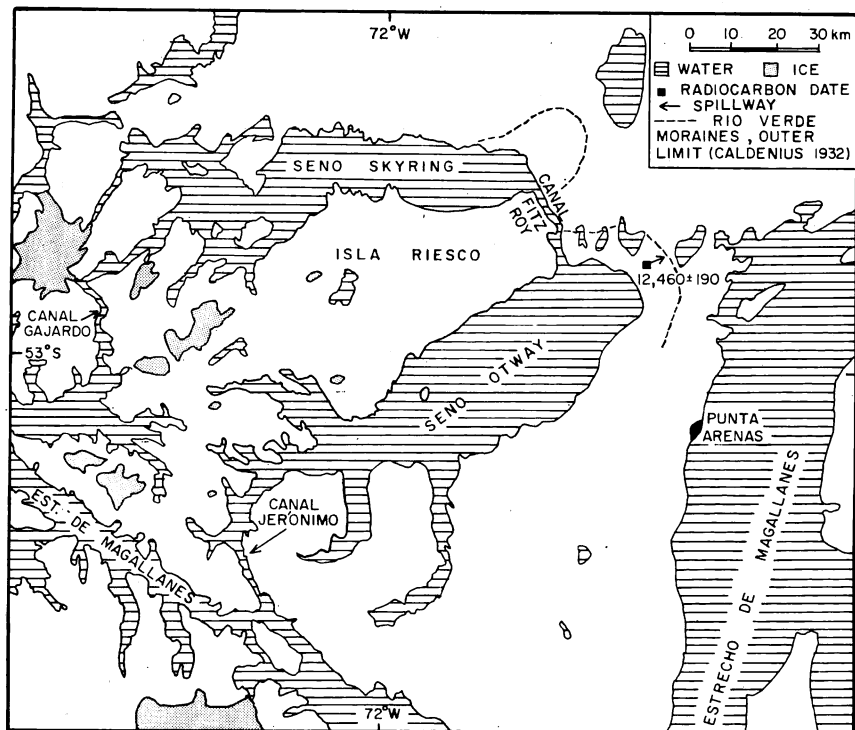


Fig. 7. Seno Skyring, Seno Otway, and vicinity.

by channels through the mountains: Seno Otway by the Canal Jerónimo, less than 1 km wide at its narrowest, and Seno Skyring by the Canal Gajardo, which narrows to 400 m. The Canal Fitz Roy connects the two embayments at their eastern ends.

Massive end moraines, the Río Verde moraines of Caldenius (1932, p. 36), form a belt about 10 km wide immediately east of Seno Otway and Seno Skyring. Soon after the ice had begun to recede from the innermost of these moraines, Skyring ice lake drained into Otway ice lake by the Canal Fitz Roy, and the combined drainage from both lakes flowed northeast by a spillway through the moraines. This spillway is accordant with a pronounced shoreline at about 20 m above sea level round the east end of Seno Otway and was occupied until the Canal Jerónimo 100 km to the west had been deglaciated. Aerial photographs suggest that a readvance interrupted the recession from the Río Verde moraines before the ice finally withdrew into the mountains, but a close examination of the western half of Seno Otway is needed to decide this point.

A lake or string of lakes apparently occupied much of the spillway after it had been abandoned, for lake clay was encountered below 2 to 3 m of peat in all trial pits except close to the spillway threshold

where peat rested on cobbles 1.4 m below the surface. At about 40 cm depth in this pit was a 6-cm-thick layer of volcanic ash. The age of the basal peat, which postdates the deglaciation of the Canal Jerónimo, is $12,460 \pm 190$ C-14 yrs (I-3512).

Changes of level in Seno Skyring and Seno Otway since the ice receded from the Río Verde moraines require further study to determine their significance. The Canal Fitz Roy, which deepens steadily from 20 m at the Seno Skyring end to 30 m at the Seno Otway end, must have been cut to that depth at a time of low sea level, after the Canal Jerónimo sea connection had been opened, but when the Canal Gajardo was still closed by ice. Marine shells up to 6 m above present sea level indicate a later transgression, followed by emergence. The relative importance of eustasy, isostasy, and tectonic movement in these changes is uncertain.

THE CHRONOLOGY

The Patagonian Late-Glacial ended early, and the ice then shrank rapidly to within its present borders. Three Neoglacial readvances of glaciers on the west side of the southern Patagonian ice field followed a long Hypsithermal Interval.

Late-Glacial and early Postglacial times.—According to the definition given previously (Mercer, 1968, p. 91) and earlier in this paper, the Patagonian Late-Glacial ended when the ice on the east side of the mountains began to recede from the youngest end moraines beyond the confines of the mountains. No equivalent features have been recognized on the west side of the southern Patagonian ice field, but they are perhaps present near the outer coast. The type deposits of youngest Late-Glacial age are the Punta Bandera end moraines of Lago Argentino (fig. 1), which are comparatively small-scale features about halfway between the present ice fronts and the 10-km-wide belt of massive end moraines round the east end of the lake (Mercer, 1968, p. 95). Similarly situated moraines are present at Lago Viedma, 75 km to the north. A short, cool episode of regional occurrence—the Punta Bandera Stade—is inferred from this evidence but has not yet been demonstrated.

Three hundred km to the south, aerial photographs of the western shores of Seno Otway and Seno Skyring show features that are perhaps moraines of Punta Bandera age. Caldenius' (1932, pl. 42) correlation of the 10-km-wide Río Verde moraine belt at the east ends of these lakes with the Punta Bandera moraines seems unlikely in view of the great disparity in scale and the contrast in setting; in these respects the Río Verde moraines resemble those round the east end of Lago Argentino, and a similar age seems probable.

Caldenius (1932, p. 155-157) concluded from varve "teleconnexions" that the Río Verde moraines were correlatives of the Middle Swedish moraines, and he referred to them as "Finiglacial" in age. The Middle Swedish moraines were formed in Younger *Dryas* time, about 10,800 to 10,300 B.P. Auer (1956, p. 217-218), however, concluded that the Patagonian glaciers had already retreated almost to their present margins

before Finiglacial time. His evidence was mainly the distribution of volcanic ash layers that he believed were Late-Glacial and also the age of material from the Mylodon cave, which lies within Caldenius' alleged Finiglacial moraines. This age (two dates: $10,800 \pm 570$ B.P. and $10,864 \pm 720$ B.P.; Arnold and Libby, 1951, p. 120) would be about 200 yrs greater if corrected for the Suess effect.

The deglaciation of the Canal Jerónimo by about 12,500 B.P. and the shrinkage of the Glaciar Tempano to within its present margins by 11,000 B.P. confirm Auer's conclusion about early recession of the ice into the mountains. The Punta Bandera Stade, the final episode of the Patagonian Late-Glacial, is known to date from before 10,000 B.P. (Mercer, 1968, p. 106), and, because it affected a more extensive ice cover than existed when the Canal Jerónimo was deglaciated, it almost certainly occurred before 12,500 B.P. This suggests a possible correlation with the final advance of the Otira Glaciation in New Zealand during the Kumara 3 Stade, tentatively dated at 14,500 to 14,000 B.P. from organic layers in river gravels (Suggate, 1965, p. 84). However, during the Kumara 3 Stade the New Zealand glaciers were much closer to their Full-Glacial extents (Suggate, 1965, fig. 22) than were the Patagonian glaciers during the Punta Bandera Stade, indicating that the Kumara 3 Stade is probably the older. Correlation of the Punta Bandera Stade with a New Zealand episode must await further C-14 dating from both areas.

Although Auer (1956, p. 218) concluded that Caldenius' alleged Finiglacial (Younger *Dryas*) moraines were older, he inferred from the pollen spectra in Fuego-Patagonia that the glaciers did indeed readvance in Younger *Dryas* time. He believed that the moraines of this age lay within the mountains, not far from the present ice fronts. Since Auer wrote, however, most of the dated moraines near the present glaciers have been shown to be less than 5000 C-14 yrs old (Mercer, 1968, and this paper). Only the Bernardo is known to have a moraine more than 5000 yrs old in the vicinity of the present ice front. (The ridges above the Tempano with basal peat 6010 ± 120 C-14 yrs old between them were, because of their subdued relief and small extent, interpreted in the field as features formed during recession by brief, local fluctuations of the margin, and of no regional climatic significance. Other dates from the vicinity of the Glaciar Tempano suggest that these features in fact probably date from before 11,000 B.P.) The multiple end moraine above the Bernardo was thought in the field to reflect a thickening of the whole glacier, because it was as large as the recent moraines and extended for a considerable distance along the hillside. The age of the basal peat, $10,000 \pm 160$ C-14 yrs, indicates that the moraine could be of Younger *Dryas* age. However, the absence of comparable end moraines in front of any of the other glaciers studied indicates that no regional readvance occurred. The moraine is perhaps considerably older than the age of the basal peat suggests, probably because the peat was obtained from the side, not the bottom, of a depression; it may have been formed during fluctuations of the receding glacier before 11,000 B.P.

The age and significance of the Puerto Eden end moraine is uncertain, but it must be older than the basal peat age of 9670 ± 160 B.P. suggests. Ice cover on Isla Wellington today is confined to a few small glaciers on peaks more than 1200 m in elevation, whereas the Puerto Eden moraine was formed near sea level by a 15-km-long glacier. Therefore it must antedate the withdrawal of the mainland ice to its present margins before 11,000 B.P. However, no end moraines of the mainland glaciers are known between those near the present ice fronts and Puerto Eden, suggesting that the Puerto Eden moraine was not climatically caused. Probably it was formed immediately after the channel between Isla Wellington and the mainland became ice-free, thus stranding former tributary glaciers at the valley mouths. Therefore, the Puerto Eden moraine is likely to be Postglacial as defined earlier but must date from well before 11,000 B.P. The age of the basal peat is probably misleadingly low, because it was obtained from an open slope, not from an enclosed hollow.

In New Zealand also, no correlative of the Younger *Dryas* Stade has been demonstrated (Suggate, 1965, p. 84). Mercer (1969) suggests that the stade was caused by a sudden change in ice conditions in the northern North Atlantic and was essentially confined to Europe, although mild repercussions might have occurred elsewhere.

Hypsithermal Interval.—The Patagonian Hypsithermal Interval is defined as the Postglacial interval that began when the climate first became warmer than it is today and ended when it became cooler. Temperature changes are inferred from glacier fluctuations. Mercer (1968, p. 107) suggested that the Hypsithermal Interval in Patagonia continued after the first Postglacial readvance which, therefore, was an interruption of the Hypsithermal Interval and was not a part of Neoglaciation as defined by Sharp (1960, p. 321). However, it now seems likely from evidence presented in this paper that warmth returned for no more than several centuries, and even though hypsithermal conditions perhaps prevailed again for a time, it is more reasonable in this area to consider that the Hypsithermal Interval ended before the first Postglacial readvance which was, therefore, part of Neoglaciation.

The advanced state of deglaciation by 12,500 B.P. indicated by the opening of the Canal Jerónimo suggests an early start to the Hypsithermal Interval in Patagonia, and this is confirmed by the recession of the Glaciar Tempano to within its present borders before 11,000 B.P. The Tempano is a typical outlet of the ice field, and its fluctuations probably reflect the regional climate. Thus the Hypsithermal Interval may have lasted the entire six millenia 11,000 to 5000 B.P. No data are available to suggest when the warmest part of the interval occurred. The end of the interval at about 5000 B.P. is an estimate based on the date of the culmination of the following readvance. About 200 km to the north the Glaciar San Rafael, an outlet of the northern Patagonian ice field (fig. 1) was smaller than it is now about 6850 ± 200 B.P. (Heusser, 1960, p. 570).

The Patagonian ice was already less extensive than it is today at a time when the Laurentide Ice Sheet in North America extended as far south as the Great Lakes, and the European ice sheet covered most of Scandinavia. This suggests that present levels of warmth were reached in the southern hemisphere at least 2000 yrs earlier than in much of the northern hemisphere, probably because no melting ice sheets were present to retard recovery. However, although the northern hemisphere ice sheets were heat sinks that primarily affected the climates of the northern hemisphere, they must have had a cooling effect on the entire world. This has an important implication: if the Patagonian climate in 11,000 B.P. was warmer than it is today despite the existence of these heat sinks, the cause of the warming must then have been considerably more effective than it is today.

First Neoglacial readvance.—Basal peat is 4060 ± 110 C-14 yrs old on the second oldest end moraine of the Glaciar Ofhidro Sur, which therefore reached the oldest moraine not later than about 4200 B.P., allowing for an estimated 50 yrs age difference between the moraines and for a 100 yr interval before the start of peat growth. The glacier probably remained larger than it is today for at least 300 yrs, with several oscillations of the front, because the sixth moraine is more than 3740 ± 110 C-14 yrs old. Peat 4120 ± 105 C-14 yrs old covering a feature exposed after the maximal extent of the upper part of the Glaciar Tempano indicates that this glacier readvanced at about the same time as the Ofhidro Sur.

The greatest Postglacial readvance of the Glaciar Hammick culminated at an uncertain date. Because no sites suitable for obtaining basal peat were found on the old, thickly wooded moraine ridges, samples were obtained immediately outside the three oldest moraines, on outwash that was believed to have become stabilized soon after the ice had begun to recede from the moraines; ages were 3110 ± 130 , 2300 ± 110 , and 2070 ± 95 C-14 yrs. However, although these dates are internally consistent and must reliably indicate minimal ages for the moraines, the outermost moraine must be considerably older than 3110 yrs because a tree that grew for 300 yrs 3 km away near the present terminus died about 2800 ± 100 B.P., implying that the site it grew on was ice-free in 3200 ± 100 B.P. The second moraine appears, from the amount of dissection it has suffered from meltstreams, to be much closer in age to the first moraine than to the third. Tentatively, both the first and the second moraines are assigned to the first Neoglacial readvance, but their true ages are not known.

The estimated dates of about 4200 to 4300 B.P. for the culmination of the greatest Postglacial readvances of the Glaciar Ofhidro Sur and the upper part of the Glaciar Tempano are similar to, or slightly later than, those of the Glaciar San Rafael 200 km to the north, before 4000 B.P. (Heusser, 1960, p. 568); the Glaciar San Lorenzo Este, 200 km to the northeast, about 4600 B.P.; and the Glaciar Narvaez 150 km to the

east, before 4320 B.P. (Mercer, 1968, p. 94). Glacier advances elsewhere in the fifth millenium B.P. are discussed by Mercer (1967) and Page (1968).

Second Neoglacial readvance.—The Glaciar Ofhidro Sur was still larger than it is today when a recessional moraine of the first Neoglacial readvance, with basal peat 3740 ± 110 C-14 yrs old, was formed. The age of a recently exhumed stump of a mature tree situated 50 m from the present front of the Glaciar Hammick indicates that this glacier was smaller about 3200 B.P. than it is now and was readvancing about 2800 B.P. Thus the warm interval between the first and second Neoglacial readvance probably did not last more than a few centuries.

The readvance of the Glaciar Hammick perhaps culminated before 2300 B.P. at the second moraine and was followed by recession and readvance to the third moraine; however, for reasons given earlier, the second moraine is likely to be older than the age of the basal peat suggests, and the readvance probably culminated at the third moraine sometime between about 2700 and 2200 B.P. No other moraines of this age are known from the field area, but unvisited moraines of the Glaciar Ofhidro Sur date from after 3740 ± 110 B.P. Readvances after 2800 B.P. are known from many parts of the northern hemisphere (Porter and Denton, 1967).

Third Neoglacial readvance.—Stumps close to the present margins of the Glaciar Bernardo and splintered by overriding ice between the mid-15th and the mid-18th centuries A.D. and forest debris extending beneath the ice of the Glaciar Tempano are evidence that these glaciers have recently readvanced from retracted positions. Stumps buried by the outwash of the Glaciar Ofhidro Norte about the beginning of the 14th century A.D. indicate that this glacier was increasing in volume for several centuries before it reached its maximum. The only absolute date for the culmination of the readvance is about A.D. 1760 for the Glaciar Tempano, obtained from a tree-ring count of a single, ice-tilted, still living tree. If an interval of about 70 yrs was everywhere necessary before tree seedlings could become established on deglaciated ground, as was apparently true near the Glaciar Tempano, all the glaciers studied reached their greatest extents between about A.D. 1750 and A.D. 1800.

Several recessional readvances followed the late 18th century maximum. The most recent, which affected all the glaciers visited on the west coast, is now marked by an unvegetated moraine. In 1945 the aerial photographs show that the glaciers had receded slightly from a fresh moraine or trimline, indicating that the maximum may have been reached in the early 1940's. However, the complete absence of vegetation on the innermost moraine suggests that the ice may have resumed its advance after 1945. Some glaciers were perhaps advancing as recently as 1958-1959, at the same time as the Glaciar San Rafael 200 km to the north (Heusser, 1960, p. 563), but the great recent shrinkage of the Glaciar Ofhidro Norte and Glaciar Tempano suggests that these glaciers reached their maxima earlier. In 1968 all the glaciers were receding, but they were much closer to their maxima of recent centuries than were most

of the glaciers on the east side of the mountains (compare pl. 2 and 4 with Mercer, 1965, fig. 9).

At their maxima of recent centuries, the Glaciar Ofhidro Norte, Glaciar Ofhidro Sur, and Glaciar Hammick were considerably smaller than during earlier Neoglacial advances. This is also the general pattern on the east side of the mountains (Mercer, 1968, p. 107). On the other hand, the lower part of the Glaciar Bernardo apparently reached its greatest Neoglacial extent in the 18th century (the higher parts were not visited), and the 18th century maximum of the Glaciar Tempano slightly exceeded that of the fifth millenium *B.P.* along the lower part of the glacier, but not at higher elevations. However, the advanced positions of the tongues of these two glaciers during recent centuries were perhaps not entirely climatically caused but were partly determined by changed interaction of the glacier fronts with tidewater, the Bernardo because of the construction of an outwash plain, and the Tempano because of a rise in sea level. Glaciar Bernardo is separated from Fiordo Bernardo by a narrow outwash plain of recent origin (pl. 2) and was probably formerly a calving glacier. Later, it greatly reduced its ablation losses by building a protective outwash plain and was thus able to terminate in a more advanced position than when it was a calving glacier. The terminus of the Glaciar Tempano reached an abrupt widening of the fiord at its 18th century limit (pl. 3 and fig. 5) and probably could have reached little further forward during earlier Neoglacial readvances. Thus if sea level were lower—and drowned trees throughout the area attest that relative sea level has risen at least 2 m during recent centuries—the long profile of the glacier would have been steeper. This could explain why the 18th century moraine, which lies below the fifth millenium *B.P.* moraine along the upper part of the tongue, approaches it further down and apparently overrides it close to the terminus.

CONCLUSIONS

Before firm conclusions can be drawn about glacier fluctuations and, by inference, about the climatic sequence in Chilean Patagonia, more dated samples from more glaciers are needed. The available data suggest that since Late-Glacial time the glaciers have fluctuated in phase with, and in a similar manner to, those of Argentine Patagonia. Neoglacial fluctuations have been approximately in phase with those in the northern hemisphere but have differed in magnitude; in particular, the readvance during the 5th millenium *B.P.*, when many Patagonian glaciers reached their greatest Neoglacial extents, was apparently a minor event in the northern hemisphere. A greater contrast was in the early rise of temperatures to present levels in Patagonia compared to the northern hemisphere. The climatic sequence in Patagonia during the several millenia after about 14,000 *B.P.* perhaps indicates what would have happened in the northern hemisphere had there been no lingering ice sheets to be melted. In other words, fluctuations of the prime cause of world-wide warming, whatever that was, are perhaps more easily recognizable

in the south temperate zone than in the north temperate zone because of the smaller time lag and less equivocal relation between cause and effect.

ACKNOWLEDGMENTS

This investigation was supported by National Science Foundation Grant GA-881 (OSURF Project 2406) to The Ohio State University Research Foundation. Field work was done during the southern summer of 1967-1968. The writer was accompanied by Mr. S. F. Anliot, Duke University, who carried out botanical studies, and by Mr. Jack Ewer, Universidad de Chile, whose navigational and linguistic skills were invaluable. The Chilean Navy is thanked for their generous offer of transport to the Patagonian channels and the Chilean Air Force at Puerto Eden for their unflinching helpfulness on many occasions during the field season. In the preparation of this paper, the writer benefited from criticisms by G. D. McKenzie.

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