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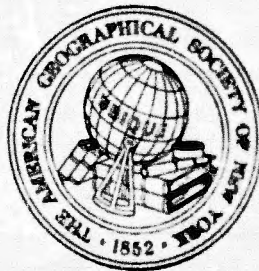
SOUTHERN CHILE EXPEDITION

1959

Technical Report

Office of Naval Research  
Contract Nonr-641(04)

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GLACIAL GEOLOGY OF THE LAGUNA SAN RAFAEL AREA

Ernest H. Muller

Technical Report

Office of Naval Research  
Contract Nonr-641(04)

American Geographical Society  
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October 1959

#### FOREWORD

This is one of a series of technical reports dealing with the preliminary scientific results of the American Geographical Society's Southern Chile Expedition 1959. The expedition was carried out in order to reconstruct the late-Pleistocene (late-glacial and postglacial) environments of southern Chile. Although data are abundant on the late-Pleistocene of North America and other parts of the northern hemisphere, relatively few studies concerned with the subject have been conducted in the southern hemisphere. The fundamental objective of this research is to uncover facts which will lead to an understanding of inter-hemispheric climatic relationships and the underlying mechanisms causing climatic changes.

This study of the glacial geology of the Laguna San Rafael area by Dr. Ernest H. Muller is the second technical report to be issued. In subsequent months, additional reports on the botanical, limnological, and palynological work of the expedition will appear.

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# GLACIAL GEOLOGY OF THE LAGUNA SAN RAFAEL AREA, SOUTHERN CHILE

by

Ernest H. Muller

## INTRODUCTION

### GENERAL STATEMENT

This paper reports on investigations of glacial geology in the Laguna San Rafael area during January and February 1959. During this field season, fundamental groundwork was laid in reconnaissance of the San Rafael area, in establishment of a partial chronology of late Pleistocene and Recent events, and in preliminary glaciological studies of San Rafael Glacier.

Ten years of investigations by the American Geographical Society on the Juneau Ice Field and elsewhere in Pacific coastal Alaska (Heusser 1958, 1959; Lawrence 1958), along with closely related Alaskan glacier studies (Olson & Broecker 1959, Karlstrom 1957) afforded the expedition basic data on glacial chronology in the west coast marine climate in the northern hemisphere. The Laguna San Rafael area in southern Chile offered comparable opportunity in the southern hemisphere, combined with ready accessibility from the sea, availability of shelter, and a reasonably long record of glacier observation.

### GEOGRAPHY

Laguna San Rafael is a tidal, but brackish and nearly land-locked, embayment of the sea at  $46^{\circ}40'$  S lat in the intensely fiorded coast of southern Chile (Figs. 1-3). It lies 150 km south-southwest of Puerto Aisen, capital of Chile's remote and sparsely populated Aisen Province. In the past it has been served by regular tourist sailings from Puerto Montt, but at the present time it is reached only by an occasional chartered fishing vessel from Puerto Aisen or neighboring ports. Yet the scenic grandeur of Laguna San Rafael is known in all parts of Chile. In 1959 it was set aside as a Park Nacional.

Foremost among the attractions of the Laguna San Rafael area is the San Rafael Glacier with its massive and gleaming sea-cliff more than 5 km long. From this constantly changing sea-wall, icebergs calve sporadically to drift to and fro in the shifting currents of the Laguna, or to escape through the Rio Tempanos (Iceberg River) before melting. Dense rain forest, composed dominantly of southern beech (Nothofagus), blankets all but the steepest slopes and climbs virtually to the snowline at about 1200 m. Partly concealed behind the low coastal mountains and visible only from the western shore of the Laguna is Mount San Valentin (4058 m), the highest peak in southern Chile. This peak stands at the north end of the extensive North Patagonian Ice Field which feeds a score of valley glaciers, among which San Rafael is one of the most striking (Grosse 1955).

Laguna San Rafael is roughly fan-shaped, with its flattened eastern shore trending about  $20^{\circ}$  east of north. Its maximum dimension, roughly north-south, is 16 km; roughly east-west, it is almost 11 km broad. Its shores are rimmed on all sides by bluffs generally less than 15 m high, cut in unconsolidated

drift. Low-lying, but rather well-drained land only a few meters above sea level lies east of the northeastern portion of the Laguna. Its basin is rimmed by a prominent compound moraine ridge. Major flow into the lake comes from San Rafael Glacier on the east, in the position of the handle of the fan. Marginal streams enter Laguna San Rafael on both north and south edges of the glacier, but their discharge is insignificant compared to the flow of meltwater and calving from the sea-cliff of the glacier. Only one other streamlet of significance crosses the moraine rim which borders the Laguna. This is "Cascade Creek" which flows from a hanging trough parallel to and a few kilometers north of San Rafael Glacier. Maximum depth of Laguna San Rafael charted by previous hydrographic surveys was 109 m (Armada de Chile 1950), but soundings with nylon line during the present investigations suggest depths of as much as 140 m, nearer to the sea-cliff (Shoji Horie, personal communication).

In 1941 the Chilean government began excavation of a canal to link Laguna San Rafael with the Golfo de Penas and so to create a sheltered waterway from central to southernmost Chile. On the east shore of the Laguna a modern tourist hotel was built to house in comfort those who might travel from far off to enjoy the attractions of the area. Wartime conditions brought abandonment of the canal project. Limited tourist interest forced closing of the hotel a year later. In 1959 nobody lives in the Laguna San Rafael area, and the nearest homestead is 23 km to the north near Punta Quesahuen.

#### CLIMATE AND METEOROLOGY

The climate of the San Rafael area, like that of southeastern Alaska, is typical of stations in mid-latitude, west-coast, marine locations (Cb climate of the Köppen classification). The dominant climatic control is position on the exposed slope of a coastal cordillera, that is subject to frequent migratory cyclonic storms. As a result, diurnal and annual temperature ranges are narrow, storms are frequent, and precipitation is abundant in all seasons.

Table 1 summarizes meteorological notes made at Laguna San Rafael in mid-summer 1959 and precipitation data at Puerto Aisen during the same period. The observations are too brief to justify more than passing discussion. Temperatures during January and February ranged between 5° and 10° C. at the hotel within a kilometer of San Rafael Glacier. Warmer temperatures may be expected at Ofqui on the west shore of the Laguna and farther from the glacier. Precipitation at the hotel during the 26-day observation period averaged 18 mm/day. Maximum precipitation on one day was 48 mm; six days were without any precipitation. Puerto Aisen had about 25% less precipitation during the same period, but the peak precipitation in a 24 hour period was 87 mm, almost twice as great as at the Laguna. Five frontal passages were recognized.

A typical mid-summer weather sequence experienced at Laguna San Rafael is as follows. After a frontal passage the wind shifts to southwest with shower activity and occasional hail or graupel during the day. A low stratiform cloud cover may develop after dark. Shower activity is less intense on the following day, with clouds scattered by evening. Fresh snow blankets the mountains down to 1200 to 1500 m. With the wind backing around to the east, clearing occurs on the following day. Fair weather occasionally persists for two or three days during the passage of a migratory anticyclone eastward south of the area. With approach of the next cyclone, the wind backs around to the north, pressure drops steadily, and a stratiform cloud deck moves in at intermediate elevation,

Table 1

Meteorological observations at Hotel San Rafael and  
in Puerto Aisen during January and February 1959.

Date	Hotel San Rafael			Puerto Aisen <sup>3</sup>
	Pptn (cm)	Temp (°C) <sup>1</sup>	Weather	Pptn (cm)
January				
11	--	--	Squalls, diminishing in PM	--
12	0.0	--	Fair	--
13	--	--	Fair in AM; rain in PM	--
14	T	--	Cloudy in AM; clearing	--
15	0.0	--	Fair	--
16	0.0	--	Fair	--
17	4.8	--	Squalls after FROPA in AM	0.0
18	3.3	--	Squalls all day	1.24
19	3.0	--	Rain all day	0.46
20	1.8	--	Light rain; increasing in PM	3.67
21	4.2	--	Rain	0.24
22	3.0	--	Rain	0.57
23	4.8	--	Rain; FROPA in PM	0.60
24	0.1	--	Rain showers; hail	8.70
25	(M) <sup>2</sup>	--	Scattered showers	0.61
26	(2.8)	--	Fair in AM; followed by showers	0.92
27	1.1	6.0	Graupel and rain showers	1.93
28	1.9	6.0	Showers; probable FROPA at noon	3.39
29	0.4	6.6	Clearing	1.36
30	0.0	8.3	Fair	0.10
31	0.0	--	Fair; morning ground fog	0.03
February				
1	0.1	--	Fair; stratus on glacier in PM	0.0
2	2.4	5.0	Showery	0.0
3	4.3	6.1	FROPA in early PM	0.26
4	3.4	4.5	Heavy showers	2.18
5	0.3	6.6	Showery in AM	0.41
6	4.01	5.5	Rain; possible FROPA	0.0
7	1.39	6.6	Showers	2.6
8	0.0	5.0	Fair	6.22

<sup>1</sup> Time of observation - usually between 6:30 AM and 8:00 AM.

<sup>2</sup> Note that "M" under precipitation column means that no reading was made on that day. As a result the precipitation for that day is totaled in on the following day when precipitation was measured (e.g. Jan. 25 and 26).

<sup>3</sup> Data from Telegraph Station, Fuerza Aerea de Chile, Puerto Aisen.

lowering rapidly and leading to steady rain for 6 to 12 hours. The frontal passage is often accompanied by squalls with driving rain and sharp gusty winds. One cyclone commonly follows another about a day apart, with the showery post-frontal precipitation of one giving way to steadier pre-frontal precipitation of the next. Each succeeding member of such a family of cyclones is apt to be a bit more intense than its predecessor until after several days, the spell of bad weather passes with incursion of a stronger push of cold air from the south, and the cycle commences anew. This rhythm appears to reflect the effect of longer-wave, slower-moving, upper-air pressure systems superposed on shallower, faster, migratory cyclones and anticyclones.

In winter, snowline drops about 1000 m, but the moderating effect of the nearby ocean prevents intensive frost action near sea level. On the shores of Laguna San Rafael, snow cover is sporadic and ponds are only intermittently frozen. Snowfall on the mountains, particularly on the windward slope is frequent and heavy. This fact, combined with length of the accumulation season, moderate summer temperatures and abundance of cloud cover makes this portion of the Andean Cordillera the ideal environment for intensive development of active, temperate glaciers.

For a more detailed and regional concept of south Chilean climates, the reader is referred to the recent compilation of climatic data by Fuenzalida (1950).

## GLACIAL GEOLOGY

### GENERAL STATEMENT

Glaciation of the west slope of the Andean Cordillera has undoubtedly been long and complex through the Pleistocene, but in the Laguna San Rafael area, late glaciation has effaced detailed evidence of preceding stages. The fact of previous glaciation is demonstrated by gross physiographic features, but its history must be studied in detail elsewhere.

Glacial features and deposits bordering Laguna San Rafael, except on the east shore, date from a late episode of the last major Pleistocene glaciation, during which interval San Rafael existed as a massive expanded-foot glacier. Moraines representing this episode enclose the basin of Laguna San Rafael and are transected by high bluff exposures near the head of Rio Tempanos.

Low moraine ridges and an extensive outwash plain, particularly well developed on the northeast shore of Laguna San Rafael, represent minor oscillations of San Rafael Glacier during the much diminished expanded-foot phase of recent centuries.

### PRE-TEMPANOS GLACIATION

Evidence of glaciation older than that in the immediate vicinity of Laguna San Rafael is inescapable in gross physiographic relationships in the highly irregular coastline of this portion of southern Chile.

Laguna San Rafael occupies part of one of the major physiographic features on the west side of the Andean Cordillera — the inundated trough which extends from Golfo Corcovado near Puerto Montt southward for some 500 km. The southern

portion of this trough includes from north to south the following bodies of water: Estuario Elefantes, Golfo Elefantes, Rada (Bahia) San Rafael, Laguna San Rafael, Golfo de San Esteban, Canal Cheap, and Golfo de Penas (Fig. 2). Continuity of this seaway is interrupted only by Istmo de Ofqui to the south of Laguna San Rafael and the "false isthmus" to the north of the Laguna.

Whatever may have been the initiating structural controls, there can be no doubt that glacial scour is responsible for the present form of the trough (Brüggen, 1950a: 233-235). The trough walls are steep and regular with abruptly faceted spurs. Tributary valleys are hanging and are characterized by catenary profiles. Trough bottoms are enclosed and deepest in or near trunk valleys entering the trough from the east.

Estuario Francisco (Cupquellan) occupies one such tributary trunk valley or fiord, joining Estuario Elefantes from the northeast. For much of the length of Estuario Francisco the depth is 225 to 250 m, whereas the more open southwestward continuation of the trough in Golfo Elefantes and Laguna San Rafael nowhere exceeds 150 m in depth. This contrast apparently results in part from the greater erosional effectiveness of constricted glacial flow. Bedrock hills at a distance from the shore west of Laguna San Rafael and the neighboring Golfo Elefantes show evidence of glacial overriding. The abrupt eastward rock slope, by contrast, represents the confining wall of a former trough glacier.

It may be inferred from these observations that, at least once, and probably a number of times through a long history of Pleistocene glaciation, the western slopes of the Andean Cordillera have been modified by an extensive transection glacier system.

Map and air photo study of the area west of Laguna San Rafael suggests that early glaciation extended at least to the Pacific Ocean coast west of the Peninsula de Taitao. It must not be inferred, however, that glacier flow was from the heart of the Andes, a distance of 125 km west to the coast. Rather, as regional snowline was depressed, the more rugged western portions of the Peninsula de Taitao with elevations above 1300 m provided accumulation areas feeding ice fields and trough glaciers which spread in all directions. The forms of Laguna Elena and Lago Presidente Rios strongly indicate scour in part by glacier flow eastward rather than westward from the central Andes.

Moraines marking positions of the ice intermediate between the limits of glaciation and the Laguna San Rafael area may well be found as mapping of the Peninsula de Taitao progresses. This probability is indicated by the character of the drainage divide between Lago Presidente Rios and the Laguna. Particularly at the head of the Rio Negro, the southeastward projecting arms of the Lago appear to terminate in a moraine belt (Keller 1949: 16).

Within the immediate vicinity of Laguna San Rafael and Rio Tempanos, a single exposure was studied which appears to represent glaciation older than that marked by the moraines enclosing the Laguna. This is at the confluence of Rio Chivo and Rio Tempanos. The section is as follows:

Peat and organic silt.	0 to 12.5 cm
Oxidized gravel.	12.5 to 75.0 cm
Pebble gravel, unoxidized; contains a few boulders at base which are pushed into and deform underlying beds.	75.0 to 320 cm
Sand.	320.0 to 340 cm
Silt, unoxidized with fine but indistinct lamination in part deformed. Coarse sand occupies a 120 cm thick channel filling about 90 cm below top of unit. Very few pebbles.	340.0 to 800 cm

(Base of above unit is concealed. About 50 m downstream along Rio Tempanos the following unit is exposed at river level.)

Till, fine sand matrix, only moderately pebbly. Pebble orientation suggestive of deposition from northeast. About 1 m thick with base concealed.

On the basis of location outside the Tempanos moraines, this till represents pre-Tempanos glaciation, but it need not be of much greater antiquity than the Tempanos moraines. The suggestion of deposition by ice moving from the northeast indicates at least a piedmont and perhaps a transection phase of glaciation, for this site is closer to the Tempanos moraines than to the corresponding moraines of Guala Glacier (Fig. 3). It is inferred, however, that deposition at this locality occurred at the very end of what must have been a complex and multiple history of pre-Tempanos glaciations.

TEMPANOS GLACIATION

Topographic Expression

A rim of land with elevation no more than 75 m and generally less than 40 m, encloses Laguna San Rafael on the south, west and north (Fig. 3). On the south it forms the Istmo de Ofqui linking the Peninsula de Taitao with the mainland. The low divide near the shore of Laguna San Rafael deflects the meltwaters of San Quintin Glacier in the Rio Lucac westward to form Rio San Tadeo at its confluence with the Rio Negro. On the west, Rio Negro is deflected southeastward and an unnamed tributary of Rio Tempanos is deflected northeastward for about 5 km peripheral to the rim of the San Rafael basin. On the north the rim forms the "false isthmus" which fails to join the mainland with the Peninsula de Taitao only by the width of the broad canal-like Rio Tempanos.

Closer inspection shows the rim of land enclosing Laguna San Rafael to consist of a very regular outer slope rising gently toward a height of land which is everywhere within about one kilometer of the Laguna. On the north, the outer slope commences below sea level where it is inundated in the broad shoals of Rada San Rafael. On the south, the outer slope is buried beneath the gravels of the Rio Lucac and other aggrading, meltwater streams flowing from San Quintin Glacier. On the west, the outer slope terminates against higher land rising toward the divide between Lago Presidente Rios and the Laguna. In general, this gently sloping portion of the rim appears to be underlain by fine-textured material, ranging perhaps from silt and clay at the distal margin to fine to medium sand at the higher proximal border.

The height of land consists of two ridges, of which the inner is truncated by the shorebluffs of Laguna San Rafael, whereas the outer is essentially continuous. A third ridge located several kilometers closer to the glacier is truncated by the shore bluffs. Although a heavy rain forest masks topographic details, the ridges are seen to consist of irregular and elongate knolls. Many swamps and small ponds occur between the two ridges, particularly west of the Laguna. Several of these were sampled for radiocarbon and pollen analyses; two were selected for limnological studies discussed elsewhere.

The structure and constitution of these ridges is well exposed in shore bluffs of Laguna San Rafael, in abandoned excavations for a canal across Istmo de Ofqui, and in the transecting stream-bluffs of Rio Tempanos. These moraines are hereafter referred to as the Tempanos moraines, and the material which comprises them, as the Tempanos drift. For San Rafael, the Tempanos glaciation was an expanded foot phase of development represented by the three marginal ridges and associated deposits as described hereafter.

#### Exposures in the Banks of Rio Tempanos

Rio Tempanos flows north-northwest for 8 km from Laguna San Rafael into Rada San Rafael, exposing in its easterly shore-bluff a continuous transect through the Tempanos moraines and outwash (Bruggen 1950 a: 238). The south end of the transect exposes glacial till; the north end contains only stratified silt and peat (Fig. 4).

Near the shore of the Laguna the bluff ranges from 12 to 20 m in height. It gives the impression of a double ridge of which the inner unit is truncated by the shore of Laguna San Rafael, while the outer and higher ridge is about 800 m north. This steep cliff exposes only till, without distinct evidence of partings and with a minimum of stratified drift. It appears to be weakly and unevenly indurated by iron oxides. About a kilometer north of the lake the till lenses into stratified drift. For perhaps 0.5 km the stratified drift consists largely of pebble gravel, with a gradual and fairly consistent northward decrease in pebble size. Finer textured stratified material occurs at the base of the bluff, suggesting that deposition began while the ice was advancing to its terminal position.

Within 1.5 km of Laguna San Rafael the bluff is less than 5 m high and is composed of stratified peat, silt, and fine sand almost devoid of pebbles. Weakly indurated blocks of this fine-textured material occurring on the beach give a superficially misleading impression of a boulder beach. The excellent sorting evident in the stratified drift and the lack of cut and fill structure

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or cross-bedding indicate a strong probability that the material was deposited in quiet water, rather than by gently flowing streams. No invertebrate fossil evidence was found to indicate that marine or brackish water was involved. Instead, as will be discussed later, it is probable that deposition took place into a fresh-water lake.

Thickness of the surficial peat increases northward as its elevation decreases, presumably reflecting more rapid accumulation under conditions of shallower water table and impeded drainage. The peat thickens to about 120 cm in a broad, open depression about 3 m above normal high tide, but thins to 30-50 cm across a low rise about 5 m above the river. Interstratification of peat and silt northward indicates oscillating depositional conditions which are discussed later. The bluff several hundred meters upstream and across from the confluence of Rio Chivo with Rio Tempanos was sampled at 10-cm intervals through a 185-cm peat section for palynological study and radiocarbon analysis (F-59-7), which may serve to date the Tempanos glaciation and succeeding events.

#### Exposures Near Ofqui

Cuts, opened during canal excavations near Ofqui about 18 years ago, exposed a west-southwest transect through the Tempanos moraines (Keller 1949: 19) which still affords more detailed data than do the bluffs of Rio Tempanos. However, lacking the sweep of the river current to keep the exposures fresh they stand less chance of preserving a suitable type section than do the Tempanos bluffs. Already, the north-facing cliff is overgrown and concealed, and the south-facing cut is concealed at the base by accumulating slopewash.

Proglacial drift is poorly exposed in the swampy western half of the portage from Laguna San Rafael to Rio Negro, but the canal cuts begin about 600 m west-southwest of the Laguna. Here a low face exposes about one meter of silt and fine sand over coarse, stratified, oxidized sand and gravel (Fig. 5).

The westernmost till exposure is about 500 m from Laguna San Rafael and till knolls are exposed in cliffs 10 to 15 m high for about 200 m along the transect. The ridge of which these knolls are a part is hereafter referred to as the Tempanos I moraine. The till is fairly pebbly, compact and dense, even though the matrix is dominantly medium to coarse sand. The till displays a semblance of stratification ranging from barely perceptible platy structure to distinct included gravelly lenses. Although the latter must be considered to be modified or water-washed drift, deposition of the former was clearly subglacial. A massive granitic erratic 5-6 m in maximum dimension is lodged in the till in such manner as to deform the stratification around the boulder (Fig. 6). To the right (east-northeast or toward the direction from which the glacier moved) the till is completely massive, without semblance of stratification. Stratification is more marked and converges down-ice from the boulder. The top of the boulder is roughly horizontal with a gravel drift or shadow of coarse cobbles in its lee. This structure is interpreted as resulting from the emplacement of the boulder downward and forward beneath the ice sheet into lodgement till plastered beneath the glacier sole in saturated condition.

The till drops steadily eastward below the level of the excavations. At about 300 m from the Laguna it is replaced by stratified drift. Directly overlying the till is stratified, well-sorted sand containing scattered boulders 30 to 50 cm in diameter suggestive of iceberg rafting. Eastward this sand gives

way to laminated silt and fine sand with scattered pebbles. This unit is slightly faulted and marked by several minor unconformities. Overlying it and separated from it by a selva of coarse sand and fine pebbles is essentially undeformed, flat-lying, pebble-free, rhythmically bedded fine sand and silt. In considerable part this rhythmite series has the regular alternation of layers suggestive of annual varves indicating deposition in fresh water rather than brackish or salt waters.

The stratified drift sequence described above is interpreted as representing deposition in a proglacial lake impounded between the ice and the Tempanos I moraine. Pebbles, cobbles and boulders sparsely scattered in the lower portion of the stratified drift section were presumably iceberg-rafted. Withdrawal of the ice resulted in decrease in coarseness of texture and bedding upward in the section. Eastward dip is inferred to be largely primary, reflecting irregularity of the lake bottom.

The stratigraphic sequence at the top of the east end of the transect strongly suggests that the gradual rise toward the shorebluff of Laguna San Rafael represents drift of a subsequent minor glacial readvance. At the top of the laminated silt and fine sand there is a gradual coarsening of texture and thickening of rhythmite pairs. Occasional pebbles occur in the well-sorted material, suggesting recurrence of iceberg rafting. Fine sand is overlain by, and lenses eastward into, coarse sand. The uppermost unit exposed in the section for about 200 m is a gravel layer which thickens and becomes coarser-textured to within about 50 m of the shore of Laguna San Rafael where it is a cobble gravel about 2 m thick. Behind the ruined shell of a cabin on the Laguna shore, the north wall of the canal cut consists of till more than 5 m thick. This is hereafter referred to as the Tempanos II moraine. This till, like that exposed 400 meters west, possesses a sandy matrix, is only moderately pebbly, is compact and firm but uncemented. It is characterized by a semblance of stratification manifested in sand and gravel lenses and in attenuated and deformed silt streaks. No uniquely water-laid elements are recognized in the section. The similarity of the two till exposures is strongly indicative of similar provenance and environment of deposition, but the stratigraphy of the excavations indicates a significant time lapse between the two closely parallel moraine ridges.

The length of the interval represented by deposition of the rhythmite units is of considerable interest as representing the duration of time between Tempanos I and II glaciations. Unfortunately, counting of the pairs is frustrated by the existence of minor erosional intervals, the apparent rising and truncation of the beds westward, and particularly by the fact that in places the rhythm seems to change from varves to micropairs representing perhaps only severe storms. In some winter layers, continuous sedimentation is interrupted by a series of such micropairs; in other cases the interruptions are so frequent as to make it impossible to distinguish winter from summer layers. Although this information is interesting as suggesting the mildness of winter temperatures during late stages of the Tempanos glaciation, it makes impossible the precise evaluation of the interval of deposition. The maximum present exposure of laminated strata, not all of which are rhythmites, is about 4 m, but Keller's sketch (1949: 19) shows the unit as extending to the base of the bluff where it is now concealed. It would seem conservative to say that the interval between Tempanos I and Tempanos II moraines involved 200 to 400 years and perhaps significantly longer.

### Exposures in Shore-bluffs of Laguna San Rafael

Shore-bluffs of Laguna San Rafael afford less conclusive basis for distinguishing Tempanos I and II deposits than do the Rio Tempanos and Ofqui transects, because the Laguna shoreline closely parallels the moraines. Support for the interpretation of two oscillations of the expanded foot phase of San Rafael Glacier is to be found in shore bluffs near Ofqui. About 600 m south-east of the east end of the canal, the shore-bluffs expose the following section:

Top of section obscured	0 to 360 cm
Till, rather stony, with medium to coarse sand matrix. Fairly firm and compact. Includes lenses of washed drift, apparently more abundant toward base than at top.	360 to 960 cm
Lacustrine fine sand and silt, laminated but not rhythmically. Truncated upper contact. Sparsely pebbly; grooved.	960 to 1050 cm
Till, similar to the upper till and including sparsely pebbly stratified drift.	1050 to 1120 cm

This exposure affords unique evidence of the slipping of beds of unconsolidated material over one another during compaction beneath an actively moving ice sheet. Wave erosion has exposed the upper part of the lacustrine fine sand and silt, revealing several bedding surfaces (Fig. 7). Three of the surfaces show fine parallel grooving similar to slickensiding. The grooving is a product of drag of pebbles contained in silt laminae slipping one over another along the bedding planes. The pebbles may have projected into the bedding planes as a result of deposition. Equally possible, compression and compaction of the bedding may have been responsible for this relationship. A distinct groove extends to the right about 12 cm from the index finger to the pebble responsible for its formation. About 3 cm forward from this pebble is the hollow from which another pebble has been eroded. Orientation of the grooving is about 10 degrees south of west, indicating clearly that deposition was by San Rafael Glacier during the expanded foot phase represented by the Tempanos moraines. It is considered that the slipping responsible for this grooving indicated a water-rich subglacial environment. Such conditions are most apt to occur, as at San Rafael, beneath a temperate glacier with impounded marginal drainage.

Northeastward from the section previously described, lacustrine sediments are exposed sporadically near the base of the bluff. It is not always possible to determine whether they occur in place of initial deposition or as inclusions within the till. In the typical situation they are deformed and contorted by glacial overriding. About 300 m southeast of the east end of the canal excavations, bluffs 15 m high expose lensing sandy and gravelly layers, with subordinate till-like units and minor inclusions of laminated silt. Such inclusions are considered suggestive evidence that the till relates to Tempanos II rather

than Tempanos I since they involve the incorporation of sediments deposited in a proglacial lake such as may have been impounded by Tempanos I moraine. The section here is interpreted as consisting largely of outwash with subordinate till representing Tempanos II.

A third moraine ridge lies concentrically east of Tempanos I and II where it arches southwest from the north shore of Laguna San Rafael. It is represented by several small, low islets composed of firm, cemented till which are being rapidly destroyed by wave erosion. A continuation of this trend as a submarine ridge is suggested by reconnaissance soundings (Shoji Horie, personal communication). Because of the apparently close relationship of this subordinate ridge to the earlier Tempanos moraines, it is here designated Tempanos III and considered to be a recessional moraine marking a minor fluctuation near the end of the expanded foot phase of San Rafael Glacier.

#### Correlative Moraines of Adjacent Glaciers

Several adjacent glaciers which rise on the slopes of Mount San Valentin (Fig. 2) in the North Patagonian Ice Field appear to have had histories comparable to that of San Rafael Glacier.

Guala trough, 20 km north of San Rafael Glacier, was carved by a trunk glacier resulting from the confluence of Guala and San Valentin Glaciers (Fig. 3). Golfo Elefantes is cut off from Estuario Elefantes and Estuario Francisco to the north by a prominent double moraine analogous to Tempanos I and II. On the north the outer ridge forms Isla Leonor and the easterly shoal which confines Paso Quesahuen. The inner ridge, correlative with Tempanos II forms Punta Celti and arcs southwestward as a chain of islands which protect the anchorage west-southwest of Quesahuen. The two moraines appear to be very close together on the south, and they form the peninsula which projects southward to Punta Leopardo, thence southeastward in a chain of islands and shoals which separates Golfo Elefantes from Rada (Bahia) San Rafael. A recessional moraine comparable in expression and position to Tempanos III projects as a submarine ridge southward from Punta Huidobro to Punta Garcia across the mouth of Guala Bay.

The old moraine ridge which forms Punta Entrada at the mouth of Bahia Exploradores is similar in aspect to the till and moraine ridge near Punta Quesahuen and Punta Leopardo.

South of San Rafael Glacier, San Tadeo or San Quintin Glacier is the major outlet from the North Patagonian Ice Field. Like San Rafael, it spreads as an expanded foot glacier today, but its outwash plain separates it from tidewater. Moraine believed to be correlative with the Tempanos I and II moraines is mapped by Bruggen (1950a: 239) west of Rio San Tadeo and Paso Expedition. The probable correlative of Tempanos III lies only 1 to 3 km west of the present margin of San Quintin Glacier.

#### OSCILLATIONS OF RECENT CENTURIES

East of the northern portion of Laguna San Rafael is a plain here referred to as the "Hotel Flats" (Fig. 6). It is more than 5 km<sup>2</sup> in area, lies within a few meters above sea level, and is distinguished from its surroundings by the absence of mature rain forest. On the north, it borders the proximal slope of

the Tempanos moraines with an abrupt vegetational discontinuity. South and west of "Cascade Creek" is an island-like inclusion of rain forest several hundred meters in maximum dimension.

Evidence of fire and of cutting by man can be recognized in places on the flats, but this tells only part of the story. Edaphic and historic conditions account primarily for the lack of rainforest vegetation. A forest tripline (Lawrence 1951) on the trough walls east of the flats with its border roughly parallel to the glacier margin (Fig. 9), confirms the interpretation that deglaciation here has been too recent for forest recovery. Throughout the flats, incipient soil development has progressed no farther than shallow penetration by iron oxides and, perhaps, nitrogen enrichment. The shoreline abruptly truncates the moraine ridges but colluvial modification of the topography has not yet become significant.

Much of the southern third of the plain, including the area on which the hotel is built, consists of parallel moraine ridges and outwash channels arching generally east-west. Directly against the margin of San Rafael Glacier is the barren floodplain of "San Rafael River" with braided channels spreading over an area more than 300 m wide. Confined against the trough wall east of the Laguna and south of the flaring foot of the glacier is a much smaller belt of parallel moraine ridges corresponding to the area near the hotel.

#### Recent Moraines

No less than 8 minor oscillations of the northwest margin of San Rafael Glacier are represented by moraine remnants near the hotel. All are minor moraines and reflect only very brief intervals of stillstand or short readvance during general retreat. Erosional modification and soil development are negligible, indicating all the moraines to be of very recent formation. Analysis of differences in stage of vegetative recovery and forest growth is treated in detail elsewhere (Lawrence and Lawrence 1959).

The outermost and oldest of the recent moraines occurs in a compound ridge, the "Cemetery" moraine, which trends northwest and passes north of the hotel. In the vicinity of the small cemetery, for which the moraine is named (Fig. 8), tenuous evidence suggests three-fold oscillation responsible for the moraine represented by closely appressed ridges superimposed on the larger trend. About 250 m east of the hotel, the complex ridge is transected by a broad outwash channel. West of the channel a two-fold nature of the ridge is suggested. Here the inner ridge becomes more sharply defined and is referred to as the "Generator" moraine. A series of small, shallow ponds occurs in the belt between the two moraines north of the hotel. The "Generator" and "Cemetery" moraines are so intimately related as to suggest very little age difference, and the complex which they comprise is interpreted as marking limits of recent glacial advance.

"Weaklegs" moraine is the most continuous and sharply defined of the recent moraines (Fig. 10). It extends from the westerly tip of the flats near the hotel to within a couple of hundred meters of the trough wall on the east, with a single interruption, part of which was produced during construction of the hotel. The ridge is generally 3-5 m high and typically is no more than 40 to 60 m broad. During the interval when the ice margin was at the "Weaklegs" moraine, peripheral drainage probably flowed between "Weaklegs" and "Cemetery" moraines, and breached "Cemetery" moraine 250 m east of the hotel.

Less continuous and less clearly defined than "Weaklegs" moraine are the moraine remnants which mark recessional positions during an oscillatory withdrawal of the glacier. Each of the ridges so identified on Figure 9 is separated from the next older by an outwash channel. Development of each outwash channel must have postdated formation of the moraines to the north, but several of the channels may have been in use at any one time. Several of the channels contain shallow, swampy, elongate lakes.

#### Modern Outwash Plain

San Rafael Glacier is bordered near its terminus on the north by a short, torrential, peripheral stream. This stream emanates from beneath the ice about 500 m east of "Veronica Creek." For several hundred meters it flows with extreme turbulence in a narrowly confined channel, rock-walled on the north and ice-walled on the south. Even during the brief interval of observation, considerable fluctuation in level was noted. The height to which vegetation was torn and damaged indicated a minimum range of about 3.5 m within the few months of the summer season. In part, this range may have resulted from temporary blocking of the channel by calved bergs; or it may have been caused by an earlier more advanced position of the ice margin which crowded streamflow against the rock wall of the channel.

Where the stream is no longer confined between glacier and rock, it spreads in numerous braided channels across a plain of its own construction. At the head of this plain a half dozen or so small bergs are commonly stranded on gravel bars or in shallowing channels. Comparison of panoramic views of the outwash plain photographed at intervals of a week to ten days shows bars and channels to be in a state of continual change, although persistence of the general pattern was noted for the limited period between first and last observations.

The outwash plain is building up rapidly enough to spread a blanket of sand over areas of stable scrub vegetation. Annual grasses were in the process of being killed off by swamping in places adjacent to the outwash plain. An outwash channel not receiving flow from the outwash plain at the time of observation contained at its margin, plants with silt-coated leaves, indicating sporadic overflow into the channel. Figure 11 is a panoramic view at the edge of the outwash plain about 75 m north of the confluence of "Veronica Creek" and "San Rafael Creek." *Pernettya* at the waters edge is not a pioneer, but rather a survivor of the present burial. The sand along the channel bank could be easily made to flow under mechanical disturbance, reflecting loose packing resulting from dumping. Sand in the foreground has been deposited during sporadic flood stage within recent months.

Comparison of photographs taken 26 years apart shows the rate at which the outwash plain has developed and built forward into Laguna San Rafael. In 1933, as shown by the photo taken by Augusto Grosse (Fig. 12), a shallow arm of Laguna San Rafael extended far enough that a boat could be worked to the eastern end of the "Island" moraine remnants with little difficulty. Today the swift, shallow channels make this difficult and impractical. In 1959 no trace remains of a gravel ridge which in 1933 projected radially for about 50 m. In 1933 a small channel carried a portion of the meltwater north of the "Island" moraine. In 1959 this channel is expanded, the next channel to the north has come into use, and the flood plain continues to spread northward.

### Stratigraphic Evidence

Exposures of till containing large logs of coihue (Nothofagus) and overlying organic material occur both near the north and south flanks of San Rafael Glacier. Since no trees of the size of these trunks grow within 150 m above the present glacier margin on the valley wall, it follows that they must be remnants of a forest developed prior to the advances of recent centuries. Accordingly, they pin down the time at which post-Wisconsin glacier growth last brought the terminus of San Rafael Glacier beyond its present position.

South of the ice margin, several interesting and significant exposures of this nature occur in shore bluffs. Along the beach for several hundred meters from the ice margin, till is exposed in shore bluffs 2 to 10 m high. The till is very sandy with numerous boulders of granodiorite and angular blocks of red, purple, and green andesite. Wood fragments occur in the till in several places. At a point about 200 m from the glacier several large trunks are exposed in the till in such fashion as to leave little doubt that the logs are essentially of local origin, involving development of mature forest prior to recent glacial advance.

Figure 13 shows a root in growing position wedged into bedrock where it was truncated by overriding ice. This relationship confirms that the large trunks were derived essentially from this location. A similarly occurring root collected nearer the present ice border has been submitted for radiocarbon dating (F-59-2) and may be expected to give a date immediately preceding the first of the recent oscillations beyond the present terminal position of the glacier.

Near the location of the previous photograph a 35-cm coihue log was exposed along the trace of a parting marked by a slight concentration of boulders and cobbles between more massive, and less stony, till layers. No weathering profile has developed in the underlying strata, though surficial staining by iron oxides characterizes the stony layers. The log must predate an advance beyond this position within recent centuries. The log was sectioned and a sample has been submitted for radiocarbon dating (F-59-1). The tree at death was 105 years old (Donald Lawrence, personal communication). Although a century-old coihue should normally be vigorous, this trunk had developed narrow, compact annual rings during its final 25 years or so of life, suggesting perhaps the more rigorous environmental conditions associated with glacial advance.

About 30 m from the ice border a pocket of interbedded peat and sand is exposed. The layers are disturbed enough that systematic sampling of a section did not seem warranted, but the evidence was suggestive of a long interval of forest development. Podocarpus as well as Nothofagus trunks were identified in these exposures.

An exposure in the bank of the peripheral stream north of the glacier margin, about 90 m west of the point where the stream emanates from beneath the glacier, was laid bare during recent high water (Fig. 14). As seen from upstream, the exposure reveals:

Coarse, bouldery till; unweathered.	0 to 250 cm
Peat and interbedded fine to medium sand with abundant organic material.	250 to 300 cm
Sand containing angular rock fragments and organic material.	300 to 400 cm

The organic layers are somewhat irregular and deformed, probably reflecting both conditions of initial deposition and subsequent disturbance during glaciation. Contained in the organic unit are logs of Nothofagus as much as 60 cm in diameter. The organic unit was sampled in more detail for pollen and radiocarbon analyses at a point downstream near the left margin of Fig. 14 where it consists of:

Peat, compact, compressed, layered; includes moss and twig material; also a log flattened to 25 x 65 cm.	60 to 85 cm
Sand and peat interstratified.	85 to 95 cm
Peat, compact, silty, finely laminated in part. Contains excel- lent leaf prints, including <u>Notho- fagus</u> . Sample submitted for radio- carbon dating (F-95-5).	95 to 110 cm
Laminated organic silt, clay and fine sand.	110 to 115 cm
Peat, silty, compact.	115 to 117.5 cm
Organic sand.	117.5 to 122.5 cm
Gravel.	

As in exposures on the south side of the glacier, this organic site contains deposits of clastic and organic material which accumulated in a forest pond before the earliest advance of recent centuries beyond the present terminus. It is hoped that the 62-cm section may provide through pollen study some evidence of the nature of the environment which characterized the interval of milder climates prior to the recent advance.

#### Historic Evidence of Recent Fluctuations

Recent fluctuations of the terminus of San Rafael Glacier indicated by previously discussed topographic and stratigraphic evidence may have occurred within the past two centuries. Reports of early explorers have been interpreted as indicating that at the time of the first explorations, the terminus of San Rafael Glacier stood east of the shore of the Laguna (Brüggen 1935, 1950a; Keller 1949; Steffen 1948). If this conclusion is justified, San Rafael Glacier advanced into the Laguna about 1750 and reached a maximum extent of 8 km in the Laguna about 1870.

Bartolome Diez Gallardo<sup>1</sup> in 1674 gave the first account of the Laguna San Rafael without mention of the San Rafael Glacier.<sup>2</sup> In 1675 Antonio de Vea

<sup>1</sup> The journals of Gallardo and de Vea have been published in Anuario Hydrografico de la Marina de Chile with notes by F. Vidal Gormaz in 1886.

<sup>2</sup> Translations of a number of historic accounts of early Spanish exploration by E. G. Lawrence are here gratefully acknowledged.

encamped in the vicinity of Laguna San Rafael and wrote of a glacier "which extends from the beach to the land inshore." No mention is made of icebergs, which are particularly noteworthy today. It is unfortunate that de Veá was not more specific in stating whether the glacier extended beyond the shore. Elsewhere he mentioned that San Rafael Glacier was visible from a considerable distance north before reaching Laguna San Rafael. To be visible from north of the "false isthmus" the glacier would have to extend beyond the mountain front and, therefore, reached tidewater. Steffen (Bruggen 1950 a: 240) suggests that San Quintin rather than San Rafael Glacier may have been seen. De Veá mentions only the one glacier, whereas, if San Rafael Glacier were visible from the north, its larger neighbor to the south should also be seen, as is the case today.

John Byron also mentions no icebergs in the Laguna during a voyage in 1742 (Bruggen 1935). Byron was a seaman of 17 years of age during the voyage and he wrote his account for publication only many years later. He did not in this journal make extensive note of physiographic observations. Icebergs today are noteworthy phenomena in the Laguna, yet in poor visibility and under suitable conditions of wind and current, they might be much less conspicuous. Accordingly the testimony of Byron affords suggestive but inconclusive evidence, like those of de Veá and Gallardo, that prior to 1750 San Rafael Glacier did not reach tidewater.

If indeed San Rafael Glacier did not reach tidewater prior to 1750, it becomes pertinent to consider where the shore of Laguna San Rafael would be under conditions of reduced glaciation. Complete disappearance of San Rafael Glacier might be expected to leave an arm of the Laguna penetrating eastward into the mountains, in the manner of Guala Bay.

For a crude approximation of the length of such an arm, we may assume uniform thickness in the last several kilometers of San Rafael Glacier. Ablation at the terminus and the flaring form of the glacier foot make the assumption of uniform thickness very conservative. At its sea-cliff San Rafael Glacier is some 200 m thick, assuming an exposed ice face of about 50 m with the base of the glacier aground in about 150 m of water. The underlying surface may well be below sea level eastward up-glacier, at least to the 200 m contour line across the glacier surface. It may be deduced, therefore, that the retreat of several kilometers from the present terminus would be necessary to prevent San Rafael Glacier from reaching the sea. Therefore, we must assume that not only was the preceding warm interval of considerable duration as evidenced by the buried forest remnants, but also, the ice advanced a considerable distance from a position significantly withdrawn from the present terminus. San Rafael Glacier of postglacial times must have dwindled to a fraction of the size it has achieved during the recent maximum.

Father Jose Garcia Alsue<sup>1</sup> in 1776 depicted the route of his travel across the Laguna San Rafael and the Istmo de Ofqui. He specifically records large icebergs floating in the Laguna and in the Rio Tempanos, identifying them as

<sup>1</sup>The journal of Garcia was published in Anuario Hydrografico de la Marina de Chile, with notes by F. Vidal Gormaz, in 1871.

derived from San Rafael Glacier. He speaks of the glacier as touching the edge of the water, from which it may be inferred that the glacier advance was then underway.

In 1871 Commander Enrique Simpson (1875), in the course of the first bathymetric investigations in the Laguna, sketched the terminus of San Rafael Glacier, showing it as a flaring tongue extending more than halfway across the Laguna, about 8 km from the east shore. Subsequent bathymetry in 1905 under the direction of Commander Guillermo Garcia Huidobro showed roughly comparable extent with the glacier terminus slightly withdrawn. Subsequent recession was rapid. Reichert in 1920 sketched a very small scale map which showed the terminus about midway between its position of 1905 and that of the present (Bruggen 1950a: 241). In the past 25 years the recession has slowed. Oscillations have been minor and the position of the outermost portion of the sea-cliff has remained relatively stable in the direct line of sight along the right pillar at the entry to the hotel (Augusto Grosse, personal communication).

The observations referred to above suggest strongly that San Rafael Glacier commenced its modern fluctuations from a much shrunken condition about 1750. During the 120 years following, the glacier terminus advanced at least 8 km, averaging more than 65 m/year. Since 1870 recession of the icecliff has been rapid, with most of the movement taking place within the first half of the present century. The recession has been at an average rate of 140 m/year and must have exceeded 250 m/year during portions of this interval.

#### SAN RAFAEL GLACIER IN 1959

No other glacier in the world reaches tidewater as near to the equator as does San Rafael. It is several degrees farther from the pole than are the most southerly glaciers in Norway and Alaska. For this fact as much as for colorful accounts of its beauty, San Rafael is widely considered one of the natural wonders of Chile. When Simpson (1875) first visited the Laguna in 1871, he thought himself the first European to see it, so obscure were records of the first Spanish explorers. Today, most Chileans know of the glacier, but very few have seen it.

#### Source

In one sense, the ultimate source of San Rafael Glacier is near the crest of Cerro San Valentin (Fig. 2), some 40 km east-northeast of the Laguna. San Rafael Glacier served as the approach route for the Argentine climbing team which in 1952 made the first ascent of this mountain, the highest peak in the Andes of southern Chile (Club Andino de Bariloche 1954). Several large glacier tongues originate on San Valentin and diverge from it like spokes from a hub to the west, north, and east. Southward, ice-flow merges into the North Patagonian Ice Field, El Hielo Patagonico Norte of Lliboutry (1956).

The North Patagonian Ice Field is an ice plateau, interrupted by nunataks and the central ridge of the Andes (Reichert 1917). It extends some 40 km east-west and 80 km north-south and conceals ridges and troughs in a medial depression between the central ridge of the Andes and the lower mountains westward toward the fiorded coastline (Bruggen 1950b). The ice plateau lies entirely above the firmline and, therefore, comprises an expanded accumulation

zone which feeds a number of large distributary glaciers. San Rafael is the northernmost among the outlet glaciers flowing westward from this ice field. As such, it measures approximately 20 km westward from ice field to the sea-cliff, an intensively crevassed ice tongue without important tributaries.

#### A New Advance

Because the rapid recession of the bulbous foot of San Rafael Glacier during the past half-century has been documented, the present expedition was surprised to recognize a sharp advance of the ice margin at the beginning of 1959.

Evidence of this sharp advance is particularly striking along the north margin of the glacier along a distance of several kilometers up-valley from the point where "San Rafael River" flows from beneath the glacier (Fig. 15). Here the ice-margin rises as a steeply convex wall fronting abruptly on scrub growth which includes coihue (*Nothofagus*) trees 15 to 20 years old. Clearly, the ice is now more extensive than at any time in the past three decades.

Eastward the contact is abrupt, but westward toward "San Rafael River" the ice margin is rimmed by fresh moraine rubble in a strip 2 to 15 m wide (Fig. 16). The young forest growth is scraped out or overthrown along the moraine rim. Trees with leaves still green are overturned and occur side-by-side with massive coihue trunks, 60 cm in diameter, disinterred from deposits of previous advance of ice. In Figure 16 one such disinterred log is to be seen in the upper left corner along with moraine rubble and uprooted vegetation. The stake beneath the glacier sole in the foreground has been shoved over on stones which supported it a week earlier when it was emplaced exactly at the ice margin. The oscillatory nature of the balance between melting and ice movement is illustrated by the 5-cm high ridge on the cobble pavement overridden in previous weeks. Movement of the ice at this lateral position near the lower end of the trough is primarily radial, rather than longitudinal down-valley.

At the northern end of its flaring terminus, San Rafael Glacier fronts on the outwash fan of "San Rafael River." Here the marginal slope is gentle, in contrast both to the sea-cliff where iceberg calving maintains a sheer wall and to up-valley where the glacier is constrained by valley walls. Even against the outwash plain active glacial flow was evident. Clearly the thin marginal ice was being impelled by active ice behind. In a glacier spur which projected several tens of meters into the outwash, a series of planes could be observed in section where ice sheared up and out, over the slower-moving ice beneath. The basal ice block though no more than 5 m thick was itself being moved under the effect of the shear. Its sole moved outward and upward, producing a concave, rising gravel surface bordered by a low gravel ridge, 50 cm high. The ice sole projected over this low ridge, thinning into a lens exposed to rapid ablation. This exposed lens melted back 8-10 cm in places within a few hours under the afternoon sun, then maintained its position overnight. Nearby an edge of the lens, subjected to less rapid ablation, showed that actually the sole of this block had moved forward at least 16 to 18 cm in the same 24-hour period. In general, no rim of ablation debris at the margin of the ice on the outwash plain was present, suggesting that here as well as up-valley the ice was at a position slightly more extended than at any time in recent years.

It is not certain whether the sea-face of the glacier also reflected the sharp though minor advance at the beginning of 1959. Severe losses by calving make the position of the sea cliff erratic. For several days at the beginning of February, a limited portion of the ice-front near the westernmost projection of the glacier extended an estimated 75 to 100 m. This temporary expansion was accompanied by thinning of the projecting portion of the ice tongue. Within a few days adjustment by calving returned the sea cliff essentially to its position of the previous month.

The sharp advance at the beginning of 1959 was undoubtedly of small consequence in the history of recent fluctuations. No adequate control exists for measurement of the total shift of the ice margin during late 1958 and early 1959. Nevertheless, data from ice caves on the north flank of the glacier show clearly that advance within the previous two months exceeded 20 m.

#### Ice Cave Observations

Two ice caves located several hundred meters east of the point of outflow of "San Rafael River" from beneath the glacier were the object of particular study. The caves are in a lateral position where the ice tongue presses against the valley side so that ice flow and glacier expansion can be expected to be less than in the unconfined terminal portion of the glacier. Flow direction of the portion of the glacier near the ice caves is northwestward toward the valley wall. Both caves probably owe their existence to the bridging effect in the lee of low roches moutonnées. The greater height of the up-stream cave results apparently from enlargement by melting at the base of a partly annealed crevasse.

Vegetation similar to that beyond the ice margin persisted in both caves. Among the surviving plants were Nothofagus nitida, Gunnera chilensis, G. magellanica, Hebe, Pernettya, and Blechnum. The largest of the Nothofagus trees was about 10 cm in diameter at a height of 35 cm above the ground. It had been bent over, but not broken, by the ice advance. The large-leaved Gunnera chilensis showed less tolerance for the new environment of cold and decreased light. Small, new leaf-buds in the process of opening were yellowed and limp; older leaves were so damaged that it did not appear the plants could long survive. The other plants appeared tolerant enough to the new conditions to survive at least through the present season, although budding and growth were severely inhibited. Hebe and Pernettya, both well behind their normal season, had flower buds incompletely opened, some of which were brown, wizened, and immature. The plants mentioned above existed on the shallow soil in rock cracks to the inner end of the ice cave, about 25 m from the ice margin. Based on examination of the vegetation it seemed clear that the ice advance at this point had been a minimum of 25 m laterally within the previous two months.

The sole of the glacier, forming the ceiling of the ice caves, was surprisingly clean (Fig. 17). Indeed, observations of the overriding sole at the ice margin, generally, showed it to be relatively clean (Fig. 16) in contrast to the rubble-choked bottoms of some glaciers. Parts of the sole were essentially free of debris, whereas other parts were flecked with mud concentrated in some cases along low points in the ceiling. Neither cobbles nor pebbles were observed imbedded in the sole. The lack of basal debris is in keeping with the thermodynamic character of San Rafael as a temperate glacier. The lack of a reservoir of cold in excess of that necessary to keep water frozen

is evident in the delicate temperature balance and makes basal melting possible. This minimizes entrainment of material into the sole in marginal areas of the glacier.

Minor differences in the character of the ice at increasing distance from the cave entrance reflect decreasing basal ablation rates at the air-ice interface. Outside the cave where the ice undergoes severe ablation losses, it is granular and easily chipped. Expansion of voids by melting and development of pits around bits of debris (kryokonitlöcher) give the ice almost a sponge-like appearance. On exposed vertical and overhanging faces as at the cave entrances, ice cups are well developed. At a distance of 5 to 10 m within the cave, ice exposed for 24 hours or so is white from melting along intergranular surfaces, whereas freshly-exposed ice is clear and firm. More than 10 m within the cave slow ablation brings intercrystalline faces and parallel striation due to crystal structure into relief.

The ceilings of both ice caves are finely fluted with long, parallel grooves and ridges (Fig. 17). The downward projecting ridges are typically dark with flecks of mud, whereas the grooves are clean. The transverse profile of the grooving faithfully represents the form of the underlying rock surface, indicating fluting to be a type of extrusion feature. In the more westerly of the two caves, continuity of the fluting is only interrupted toward the entrance by ablation-produced ice cups.

In the second cave, some of the more pronounced ridges are segmented, breaking away in downward curving tongues. Loops of twine knotted tightly around several of the tongues were observed 7 days later (Fig. 17). The slack in the loops indicates the very modest thinning of the tongues which occurred in a week. During the same interval the tongue had moved parallel to the fluting approximately 150 cm. It had simultaneously bent down with tighter curvature, gradually pulling away at the fixed end under the force of its own weight.

#### Moraine Deposition

By preventing terminal stagnation, calving minimizes concentration of debris by ablation near the sea-face of San Rafael Glacier. For this reason, the extensive triangular area of superglacial debris on the north side of the lower portion of San Rafael Glacier is particularly conspicuous. Air photographs taken about 10 years ago show a medial moraine in this position as a relatively inconspicuous though continuous streak of dirty ice derived apparently from within the North Patagonian Icefield at the head of San Rafael Glacier. Today the triangular area is black and sharply differentiated from the inconspicuous up-glacier trace of the medial moraine. No such contrast is apparent on the air photographs. Views of the glacier terminus taken in 1940 by Augusto Grosse similarly show no particularly heavily coated or black portions of the terminus. Clearly the debris cover is presently heavier and more extensive than has been typical during the recent history of the glacier.

The triangular form of the superglacial debris concentrated by ablation at the downglacier end of the medial moraine appears to result from two processes. The one is diverging flow of the glacier where it flares at the mouth of its trough; the other process results similarly in the lateral spread of material downslope on the surface of a thinning glacier margin. A steep slope on the glacier in the area of ablation debris was observed. The slope was pocked

and pitted under a sand and silt layer. A thin cover of mineral material accelerated melting by absorbing insolation. At the top and bottom of the slope, debris was coarser and thicker; in many areas the debris was thick enough to provide a degree of insulation. As a result, the steep face underwent back-wasting, thereby maintaining its slope. Material at the top thus sporadically dropped free to the base of the slope. A small proportion of this movement may have been random, but under control of the marginal slope of the glacier, it became a distinct migration toward the ice margin.

The ineffectiveness of bull-dozing to throw up push moraines more than a few meters high has been recognized elsewhere. Presumably a thermodynamically temperate glacier such as San Rafael is less competent than a polar glacier in this respect. The ice margin may be effective in shoving over small trees. However, the ease with which the sole rides up over low obstructions, and the degree to which fluting conforms to detail of the underlying surface indicates the ice edge is more apt to adopt to, than to oppose, any significant force resisting it. Where the surface of San Rafael Glacier was free of debris, no notable marginal moraines were being produced.

Movement of material toward the surface in the wasting terminal zone of a glacier has been attributed to transfer along shear planes. This was not observed to be an important mechanism in the case of San Rafael Glacier. Although dirty shear planes exist, there is no evidence of movement of very coarse rubble along them. The relatively clean character of the sole, where observed overriding marginal deposits and in ice caves, suggests that perhaps this process too is less effective in thermodynamically temperate than in cold glaciers.

In view of the ineffectiveness of bulldozing, and the lack of debris in the glacier sole at the wasting margin, it is inferred that some other process must be dominant in moraine development. Below the debris-covered portions of the ice margin, the sporadic rattle and clatter of stones indicated the manner in which deposition was taking place. In small areas, the lateral moraine resembled the spoil pile of a granite quarrying operation, for only the larger boulders were falling clear to the bottom of the slope. Moraine deposition marginal to San Rafael Glacier is largely by mass wasting under the control of gravity and ablation, an extension of the process cited above as responsible for broadening of the medial moraine.

## CONCLUSIONS

1. Early glaciation in southern Chile extended westward beyond the Laguna San Rafael, probably entirely covering the Peninsula de Taitao.
2. Three moraines, here called the Tempanos moraines, mark the limits of glacier fluctuations similar in aspect to late Wisconsin moraines of Alaskan mountain glaciers.
3. Subsequent to Tempanos glaciation the ice border withdrew east of the present ice cliff.
4. In recent centuries, San Rafael Glacier expanded to a maximum extending 7 km west of the present terminus.
5. During the past 50 years, San Rafael Glacier has been in a state of fluctuating recession marked by minor moraine ridges and outwash channels on the lowlands north and south of the glacier terminus.
6. The oscillatory condition of the glacier terminus was marked by a small but sharp advance of at least 25 m early in 1959.
7. Preliminary impressions, subject to confirmation by radiocarbon and pollen analyses in progress, are that apparent similarities exist between the chronology of San Rafael Glacier and the chronologies of glaciers in southeastern Alaska.

## LITERATURE CITED

- Armada de Chile. 1950. Pta Pascadorcs - Istmo de Ofqui. Cuarteron XX. Valparaiso, Chile. Map.
- Brüggen, Juan. 1935. Informe geologico sobre la region de Ofqui. Boletin 52, Departamento de Minas y Petroleo: 1-17. Santiago, Chile.
- Brüggen, Juan. 1950a. Fundamentos de la Geologia de Chile. Inst. Geografico Militar. Santiago, Chile. 360p.
- Brüggen, Juan. 1950b. Geologia. Editorial Nascimento. Santiago, Chile. 509 p.
- Club Andino de Bariloche. 1954. San Valentin, Cumbre del Hielo Continental. Bariloche, Argentina. 48p.
- Fuenzalida, Humberto. 1950. Orografia, Clima, Hidrografia, Suelos, Biogeografia. Vol. I of Geografia economica de Chile. Corporacion de Fomento. Santiago, Chile.
- Gallardo, Bartolome. 1886. Expedition of Bartolome Gallardo, 1674-75. Anuario Hidrografico de la Marina de Chile 11:525-537. Valparaiso, Chile.
- Garcia A., Jose. 1871. Diario del viaje i navegacion hechos por el Padre Jose Garcia, 1766-1767. Anuario hidrografico de la Marina de Chile 14:3-42, Valparaiso, Chile.
- Grosse, I., Augusto. 1955. Vision de Aisen. Instituto Geografico Militar. Santiago, Chile.
- Heusser, C. J. 1958. Late Pleistocene environments and chronology of Pacific coastal Alaska. Bull. Geol. Soc. Am. 69: 1753-1754.
- Heusser, C. J. 1959. Radiocarbon dates of peats from North Pacific North America. Am. Jour. Sci. Radiocarbon Supplement 1:29-34.
- Karlstrom, T.N.V. 1957. Tentative correlation of Alaska glacial sequences, 1956. Science 125: 73-74.
- Keller, R. Carlos. 1949. La region del Hielo Continental de Aysen. Editorial Sociedad Amigos del Libre. Santiago, Chile. 136p.
- Lawrence, Donald B. 1951. Glacier fluctuation in northwestern North America within the past six centuries. Union Geodesique et Geophysique internationale, Assemblée Generale de Bruxelles 1: 161-166.
- Lawrence, Donald B. 1958. Glaciers and vegetation in southeastern Alaska. American Scientist 46: 89-122.
- Lawrence, D. B., and E. G. Lawrence. 1959. Recent glacier variations in southern Chile. Am. Geog. Soc., New York. 39p.
- Lliboutry, Luis. 1956. Nieves y glaciares de Chile. Ediciones de la Universidad de Chile. Santiago, Chile. 456p.

- Olsen, E. L. and W. S. Broecker. 1959. Lamont natural radiocarbon measurements V. *Am. J. Sci.* 257: 1-28 (Radiocarbon Supplement 1: 1-28).
- Reichert, Friederich. 1923. Cerro San Valentin. Bericht uber Expedition Hicken-Reichert, 1921. *GAEA* 1: 3-23.
- Simpson, N. Enrique. 1875. Exploraciones hidrograficas practicadas en las costas de Chile. *Anuario Hidrografico de la Marina de Chile* 1:20-48 and 1:111-154. Valparaiso, Chile.
- Steffen, Hans. 1948. Patagonia Occidental. Ediciones de la Universidad de Chile. Santiago, Chile. 586p.
- de Vea, Antonio. 1886. Expedition of Antonio de Vea, 1675-76. *Anuario Hidrografico de la Marina de Chile* 11:539-596. Valparaiso, Chile.

Manuscript Received  
8 September 1959

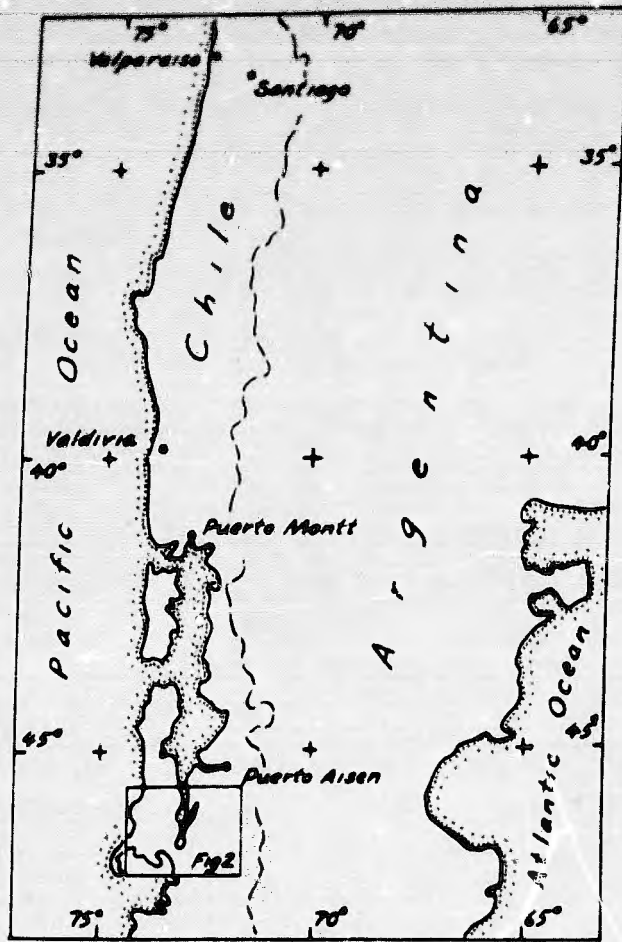


Fig. 1. Index map of Chile showing the location of Laguna San Rafael.

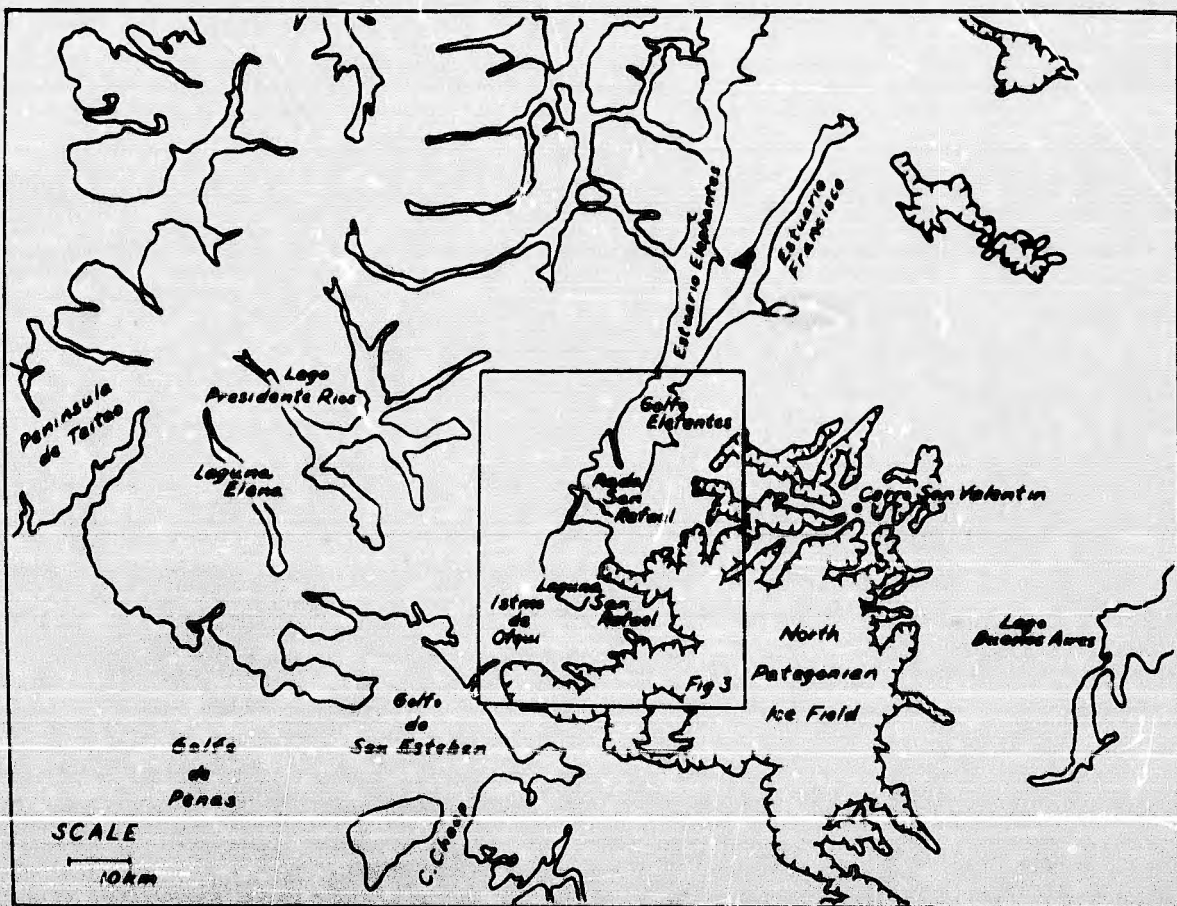


Fig. 2. Sketch map of a portion of Aisen Province showing location of place names mentioned in the text.

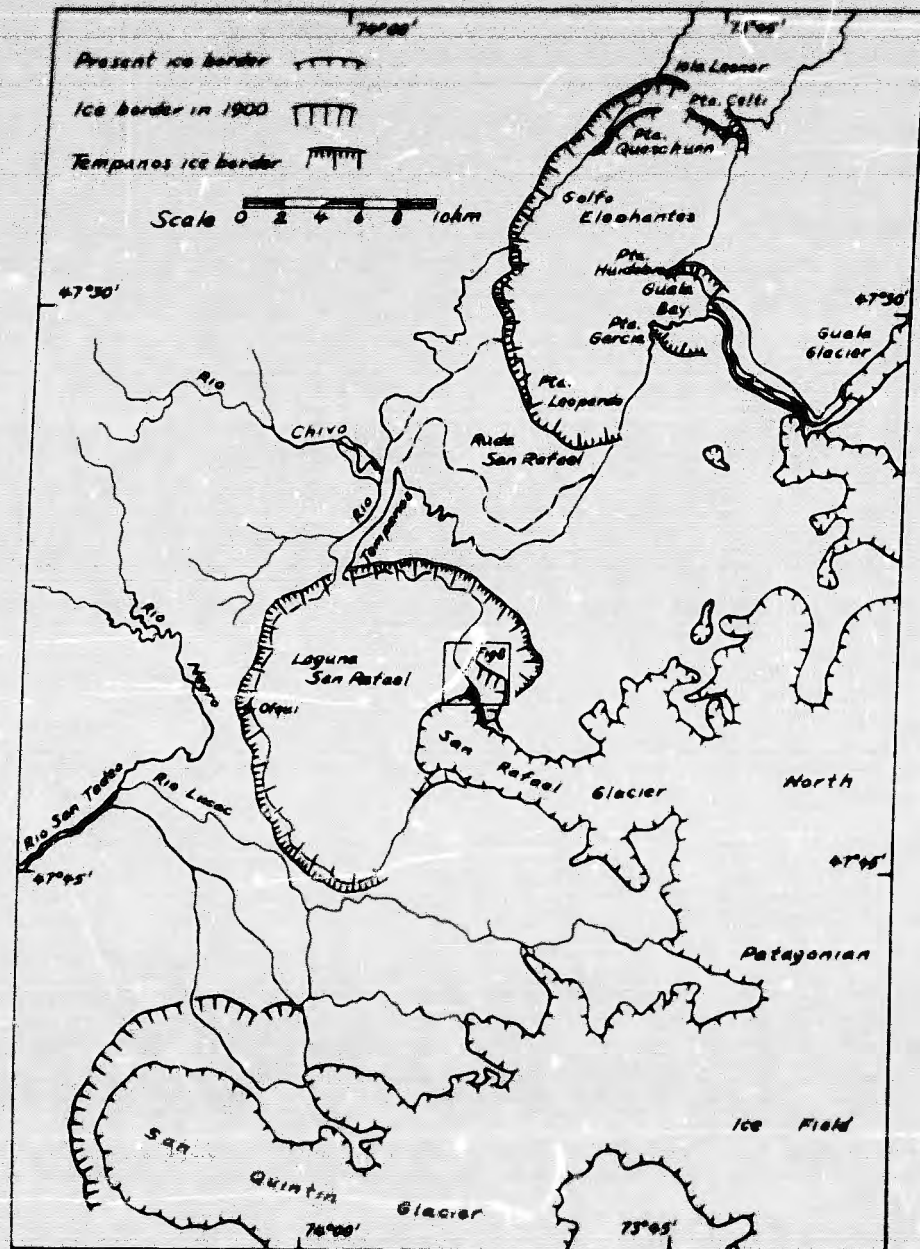


Fig. 3. Sketch map of the Laguna San Rafael area.

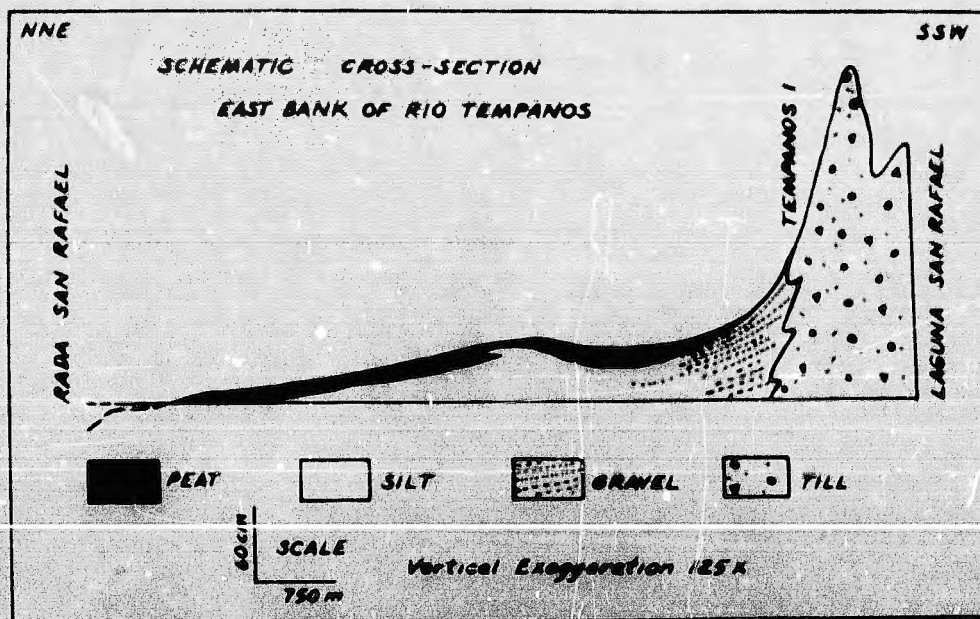


Fig. 4. Schematic cross-section showing glacial deposits exposed in bluffs of Rio Tempanos, north of Laguna San Rafael.

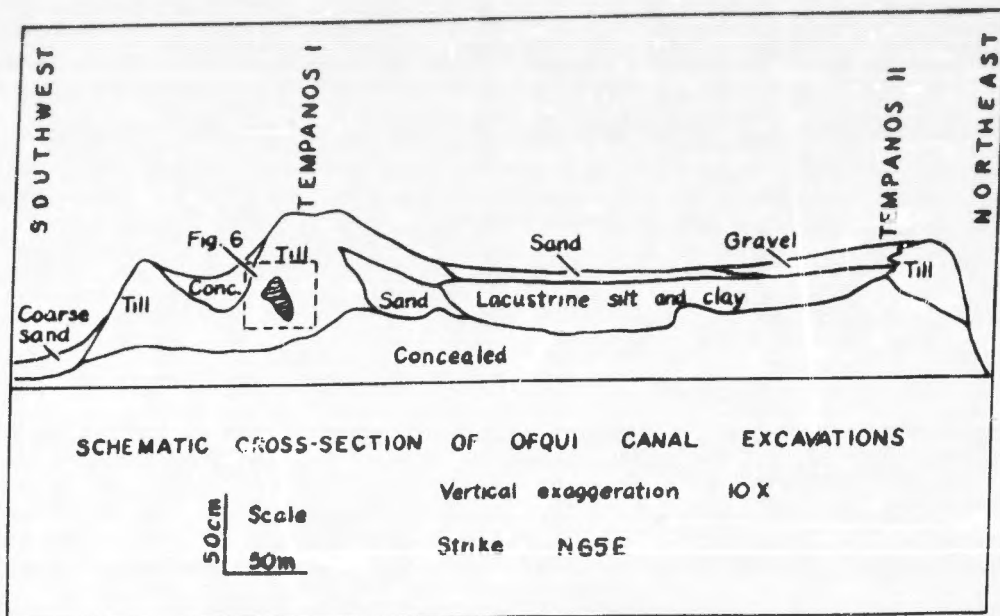


Fig. 5. Schematic cross-section showing glacial deposits exposed in canal excavations at Ofqui, southwest of Laguna San Rafael.

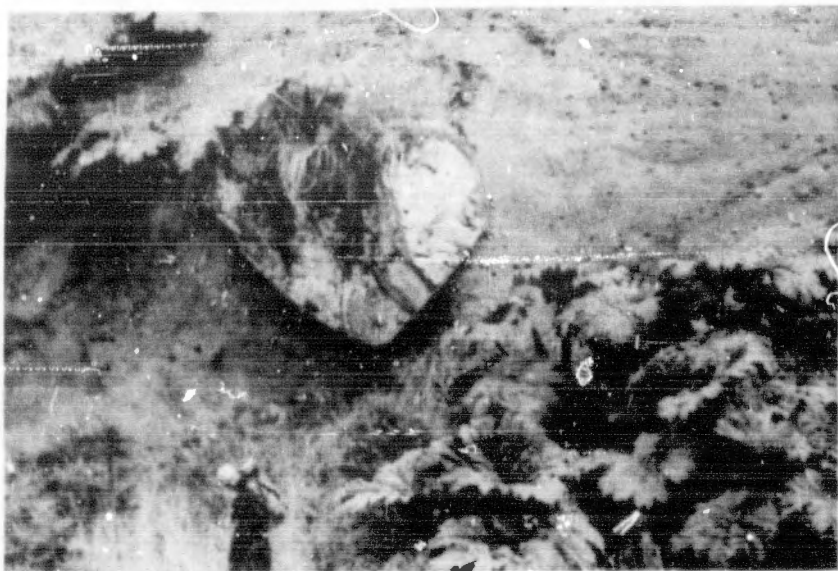


Fig. 6. Erratic boulder in Ofqui canal exposure of Tempanos I moraine. Deformation of pseudo-stratification in till shown to the lower left of boulder.

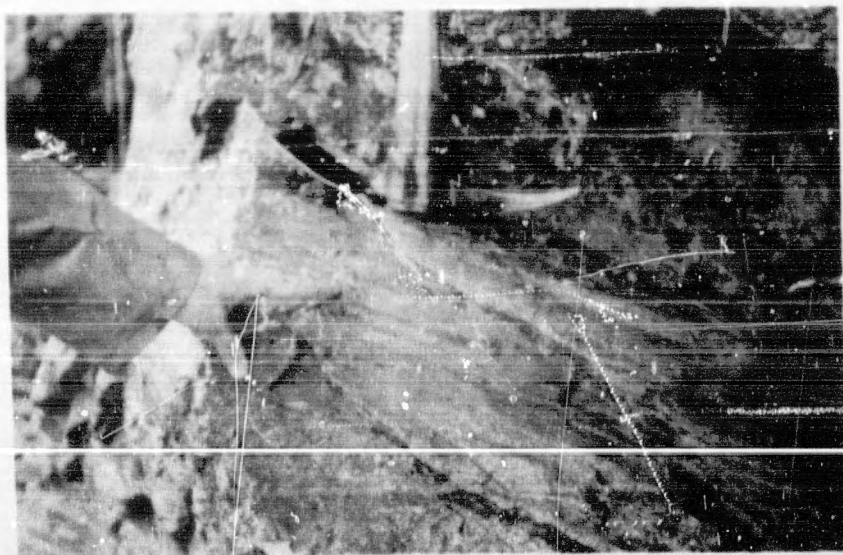


Fig. 7. Slickensiding due to glacial overriding, developed on bedding of pebbly lacustrine silt.

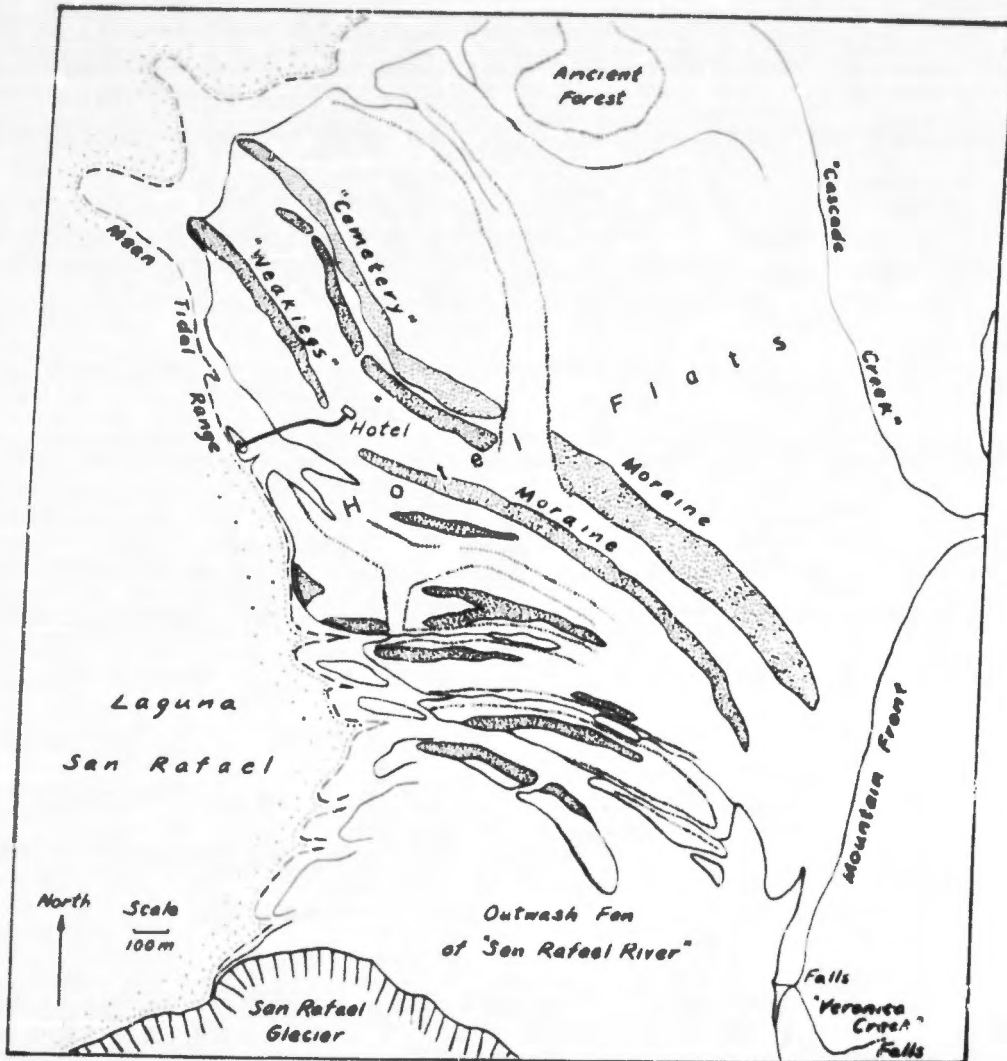


Fig. 8. Sketch map of moraine ridges (stippled) and outwash channels in the Hotel Flats area north of the terminus of San Rafael Glacier.



Fig. 9. View north of debris-littered medial moraine on San Rafael Glacier. Double trimline on valley wall reflects maximum extent of ice during two recent fluctuations, perhaps related to "Cemetery" and "Weaklegs" moraines on the Hotel Flats.



Fig. 10. Panorama of San Rafael Glacier from front steps of Hotel San Rafael. Minor moraine ridges and outwash channels characterize the Hotel Flats from "Weaklegs" moraine in the foreground to the outwash fan of "San Rafael River."



Fig. 11. Panorama of San Rafael Glacier from the outwash fan near "Veronica Creek". Aggradation by the braided channels of "San Rafael River" is burying Pernettya bushes in the foreground.

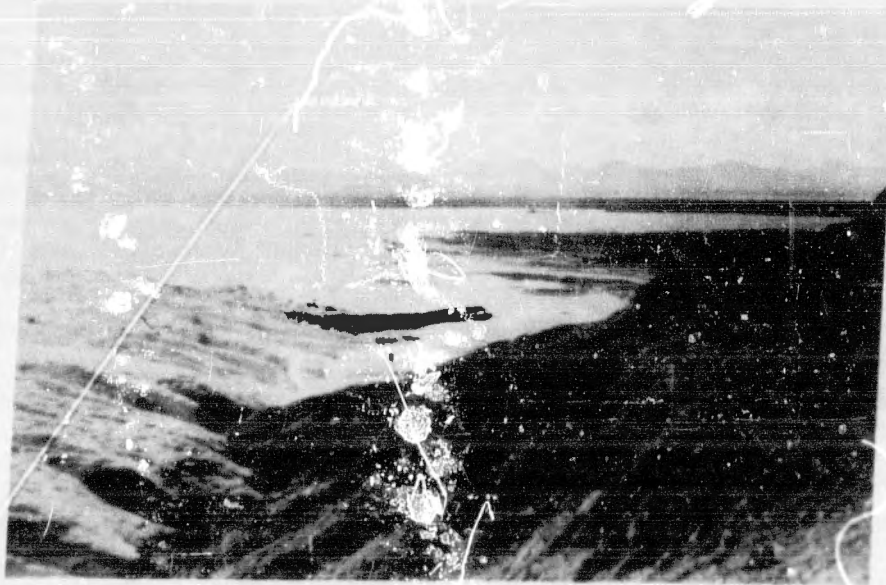


Fig. 12. Terminus of San Rafael Glacier and Hotel Flats from the east showing outwash fan in 1933. Photo courtesy A. Grosse.

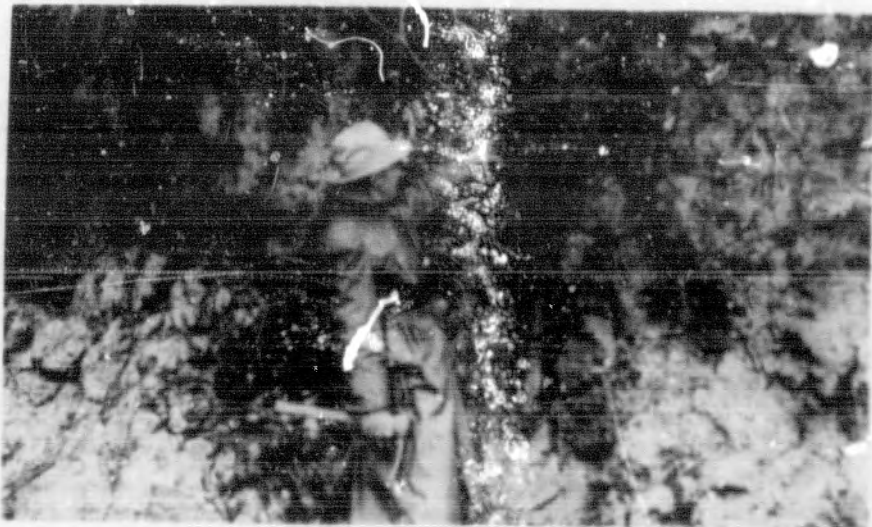


Fig. 13. Upright root in growing position, broken off and buried by overruling ice on south side San Rafael Glacier.



Fig. 14. Recent boulder till overlying peat near point of outflow of "San Rafael River" from beneath the north flank of San Rafael Glacier.

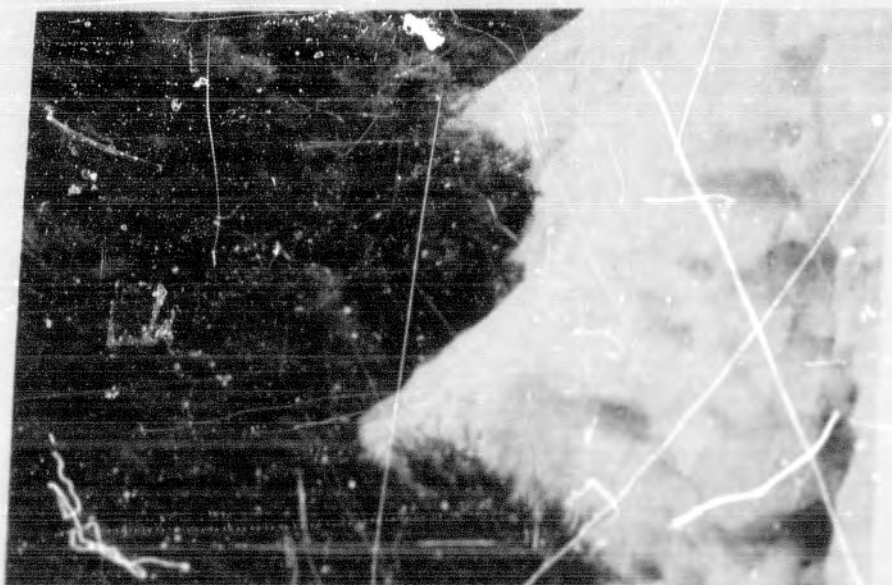


Fig. 15. Steep north margin of San Rafael Glacier plowing into Nothofagus forest in an area unglaciated for three decades. Location about 3 km east of hotel.

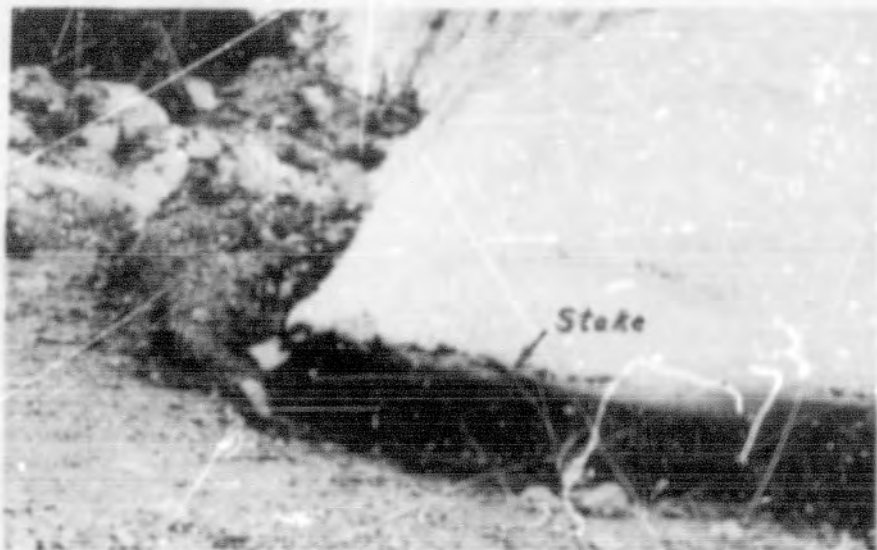


Fig. 16. Glacier sole moving over ice-planed gravel surface. Ice-shoved ridges and stake show oscillating balance between ice movement and melting.

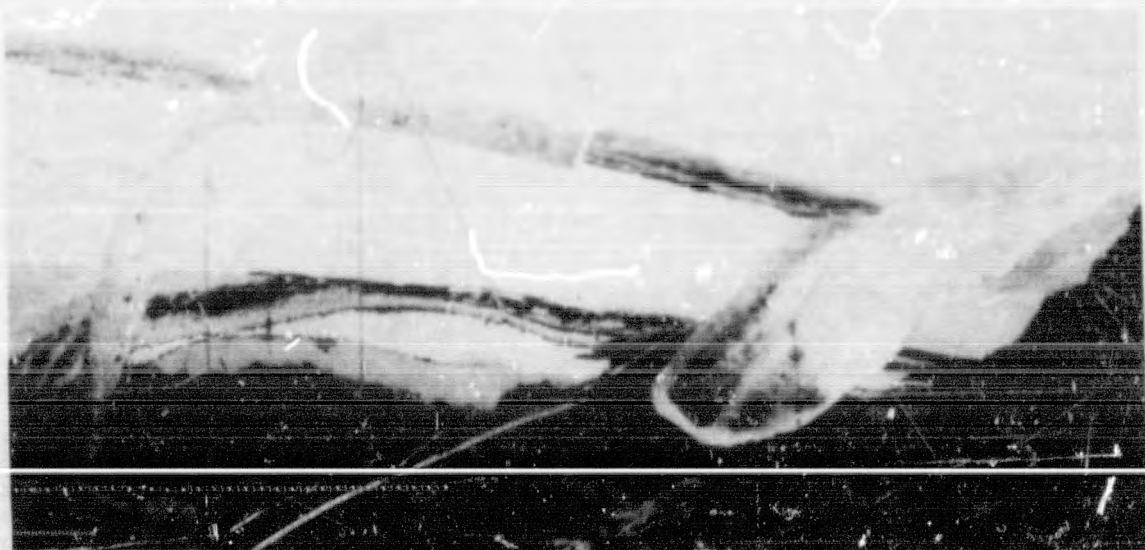


Fig. 17. Fluted glacier sole in ice cave showing downward curling ice tongues.

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