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Abstract

Evidence exists for four glaciations in the Río Blanco basin west of Mendoza, Argentina. Morphology, superposition of tills, soil-profile development, loess thickness, and boulder weathering have been the techniques most useful in mapping the tills. Glaciers of Vallecitos (= Wisconsinan) age extended to 2600 m and left distinctive moraines. Tills of two preVallecitos glacier advances cover the floor of the valley from 2600 m to below 2100 m, and remnants of one of the tills extend nearly to the junction with Río Mendoza (1400 m) 13 km below the lowest Vallecitos moraines. These deposits were considered to be mudflows rather than tills by Polanski; however, the quartz sand grains examined with SEM have surface textures characteristic of glacial abrasion. The sediments, thus, are more likely glacial than mudflow deposits. One still older till caps ridges as much as 200 m above the present valley floor. Vallecitos glaciers did not smooth the walls of the wide valleys through which they flowed; the valleys had been enlarged by the larger ice tongues during one or more of the earlier glaciations. Frost shattering of the rhyolite and quartzite has altered much of the distinctive glacial valley shape, and talus lies between the valley walls and Vallecitos lateral moraines.

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Holocene glaciations seem to be in phase with those of the Northern Hemisphere, and the Vallecitos glaciation coincided with oxygen isotope stage 2 and the Wisconsin of North America. The next older glaciation may correlate with oxygen isotope stage 6 and the Illinoian glaciation of North America. A till that underlies it is difficult to correlate and is clearly much older, but postdates the last major uplift of the range. It may represent isotope stage 12, and the period that followed it was more moist than other interglacial ages in this area. The oldest, Los Mesones, may correlate with Mercer's "Greatest Glaciation" of Patagonia, 1.0 to 1.2 m.y. ago. Although it is beyond the established oxygen isotope stages, a long cold period is present on the curves at this time, and it coincides with one of the glaciations of the "Nebraskan-Kansan" complex of North America.

Resumen

Existe en la cuenca del río Blanco, al oeste de Mendoza, Argentina, evidencia por cuatro glaciaciones. Los métodos más útiles en la identificación y el trazar un mapa de los depósitos son la morfología, la superposición de los tils, el desarrollo de los perfiles de los suelos, el espesor del loess, y la meteorización de los rodados. Glaciares de la etapa Vallecitoense (= Wisconsinan/Würm) extendieron a 2600 in donde depositaron morrenas distinctivas. Los tils de los avanzes glaciales pre-Vallecitos llenan la parte baja del valle entre 2600 m y 2100 m, y remanantes de uno de ellos extiende casi a la unión de los ríos Blanco y Mendoza, 13 km más bajo que las morrenas Vallecitoenses más bajas. Estos acarreos eran considerado por Polanski como depositos de corrientes de barro más bien que til; sin embargo, las superficies de los granos de cuarzo en tamaño de arena son fracturados para que puedan ser transportados por un glaciar. Por esto, es más probable que son los acarreos depósitos de glaciares que los de corrientes de barro. Un til más antiguo cubre caballetes que están a 200 m más altos que los arroyos actuales. Los glaciares Vallecitoense no erosionaron lisos las muredes de los valles en que se deslizaron. Durante glaciaciones anteriores, lenguas de hielo más grandes que las de la última etapa han erosionado los valles. La forma distinta glaciaria se ha alterado por el astillar por congelamiento de los cuarcitas y riolitas de las pendientes, y taludes están entre los muredes y las morrenas.

Las glaciaciones Holocénicas parecen en fase con elias del hemisferio del norte, y la glaciación Vallecitoense coincidió con la etapa 2 de los isótopos de oxígeno y de la glaciación Wisconsinense norteamericana. El til de la glaciación más antigua, la Río Blancoense, se correlacione con la etapa 6 de los isótopos de oxígeno y la glaciación Illinoianense de norteamerica. Hay dificultades en el correlacionar del til que está debajo de éste, el til Angosturaense. Claramente tiene más edad, pero depositó después de la ültima elevación del cordón. Se correlacione con la etapa 12. El suelo ahora enterrado que se desarrolló en la superficie de este til tiene rasgos semejantes a los de los suelos de áreas algos húmedas; en contraste, los suelos calcáreos indican que dos otros períodos interglaciales fueron más secos. El til de edad más grande de esta cuenca, Los Mesones, se correlacione con la "Glaciacion Más Grande" de Patagonia, descrito por Mercer, que occurrió hace 1.0 a 1.2×10^6 años. Aunque es más antigua que las etapas establecidas de isótopos de oxígeno, existe en las curvas un período largo y frío por este tiempo. También, coincide con una de las glaciaciones de complejo "Nebraskan-Kansan" de norteamerica.

Introduction

Considerable differences of opinion exist regarding the number and extent of Central Andean glaciations during the Quaternary (Corte, 1957; Polanski, 1963). Both Early and Late Pleistocene and Holocene glacial advances have been studied in Patagonia (Mercer, 1976) and in Peru (Mercer and Palacios, 1977), but the area between is less well documented. As part of their geologic mapping projects of the eastern Andean front, Groeber (1939) and Polanski (1963, 1965, 1972) studied some of the Pleistocene sediments of the Central Andes, but only a few investigations have centered on the Pleistocene deposits. Flint and Fidalgo (1964, 1969) reported on the tills of the region around Bariloche; Corte (1957) and Wayne (1981) examined some of the glacigenic sediments along the Río Blanco west of Mendoza, and Caviedes and Paskoff (1975) investigated glacial tills in two of the valleys on the Chilean side of the Central Andes.

The investigation reported on here took place in the Cordón del Plata, one of the ranges of the Cordillera Frontal in the northwestern part of the province of Mendoza, Argentina (Fig. 1). From its highest peak, Cerro del Plata (6100 m), it extends northward through Cerro Blanco (5490 m) and southwestward to the lower Cordon de Santa Clara. The crest of the range forms the divide between Río Tupungato, which flows northward to enter Río Mendoza at Punta de Vacas, and the eastward-flowing tributaries of both Río Mendoza and Río Tunuyan. Two Río Blancos drain the northern part of the Cordon del Plata; one flows northward and the other eastward.

The drainage basin studied is that of the eastward-flowing Río Blanco, which enters Río Mendoza at Potrerillos, and, in particular, two of its subbasins, Quebrada de los Vallecitos and Quebrada de la Angostura. An area of 85 km^2 is drained by these two streams above their junction.

The climate is continental, with relatively low precipitation (400–600 mm) and large diurnal temperature changes. Incomplete records for a little more than two years from the meteorological station at Vallecitos (2470 m) suggest a mean annual temperature and precipitation of approximately 5° C and 450 mm, respectively. An 8-yr record at a station near the south edge of the area, Estacion Las Aguaditas (2225 m), gives a mean annual temperature and precipitation there

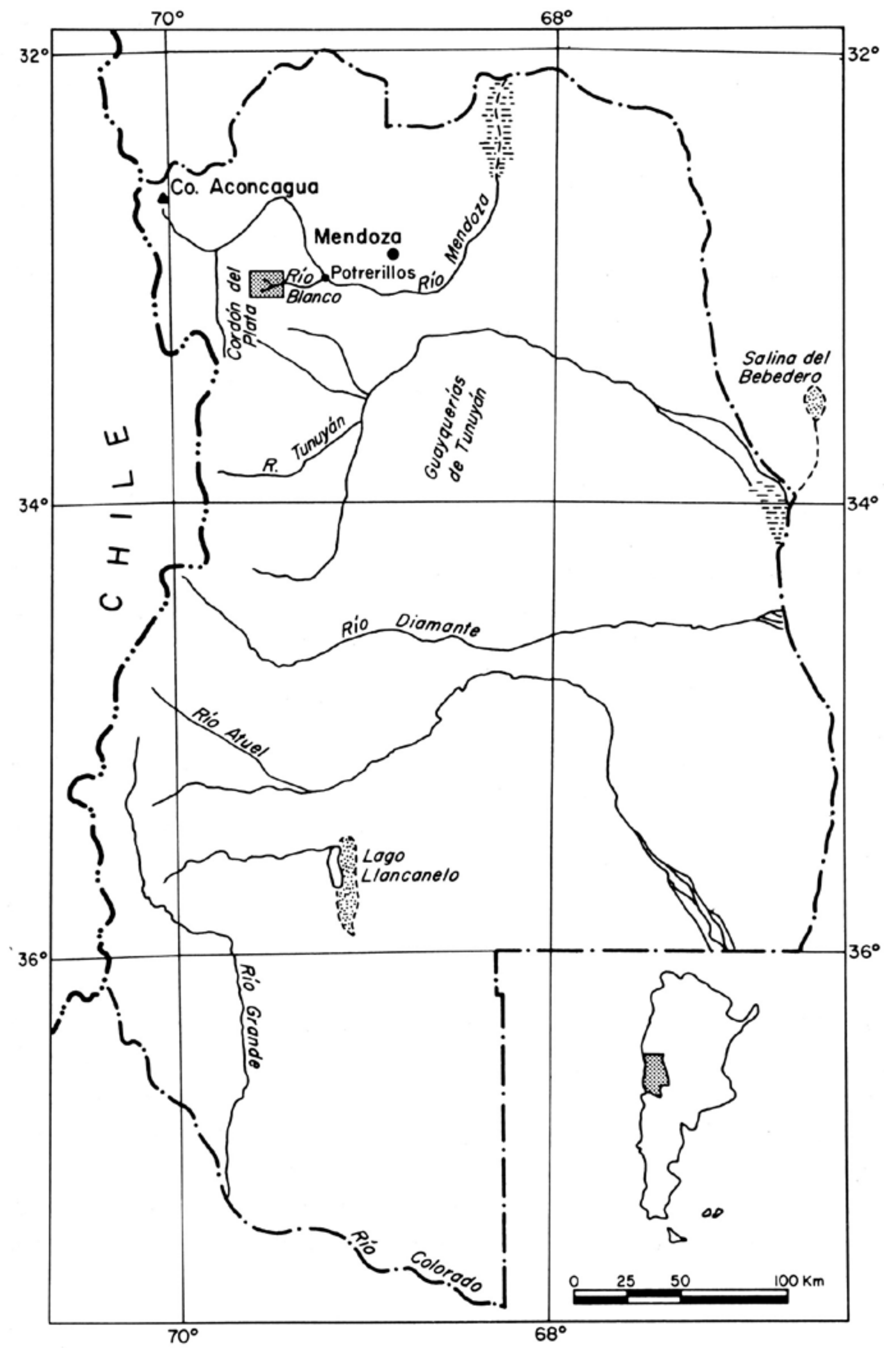

Fig. 1. Map of Mendoza Province, Argentina, showing location of area mapped.

of 7.6° C and 294 mm (Estrella et al., 1980). The altitude at which 0° C is the mean annual temperature should be 3400 m in the basin of Río Blanco, based on a lapse rate of 0.6° C per 100 m.

General Geology

Between Co. del Plata and Co. Blanco, the Cordón del Plata is composed of quartzites and related metasediments; rocks of volcanic origin, primarily rhyolites and andesites; and a few plutonic rocks. Within the area studied, the southern part is almost wholly dark-colored quartzites, but the northern part is dominated by reddish-brown rhyolites. Caminos (1965) and Polanski (1972) mapped the spine of the Cordón del Plata as the El Plata Formation, a Paleozoic quartzite more than 7000 m thick. Quartzitic rocks of the El Plata Formation dominate the slopes of Quebrada de la Angostura, Q. de los Vallecitos, and Q. Rincon, and make up some of the southwest side of Q. Stepanek. Along the southwest side of Q. Stepanek and to the northeast in Q. Colorada, the quartzitic rocks of the El Plata Formation give way to rhyolitic tuffs and andesitic breccias of the Variscan Volcanic Association (Caminos, 1965, pp. 370-378).

Plutonic rocks are not abundant. Coarse-grained biotite granite of the stock of Cuchilla de las Minas (Caminos, 1965) crops out between 3400 and 3500 m in Q. de la Angostura, and the distribution of erratic boulders in one of the moraines suggests that it is buried beneath Pleistocene sediments in Q. Stepanek. Weathered granitic rocks also crop out on the slopes near the junction of Vallecitos and Angostura Creeks. The only other plutonic rocks recognized are medium- and coarse-grained diabasic gabbros, which occur as dikes.

Geomorphic Framework

From Co. del Plata northward, most of the crest of Cordón del Plata is an arete punctuated by a few horns. At Co. del Plata, though, it includes broad sloping surfaces of cryoplanation below which glaciers have gouged the valleys. All valleys show clear evidence of having been enlarged and scoured by glacial ice, but frost shattering, avalanching, and scree deposition have altered the once-smooth U-shaped valley walls. Nevertheless, polished and striated rock surfaces can be seen in some places between avalanche chutes and cones and on bedrock high in the valleys. The cirques that head along the main ridge of the range contain small glaciers, the distal parts of which are covered with debris. The lower parts of the main valleys of Angostura and of Vallecitos are largely filled with moraines deposited by moving ice, although small rock glaciers have formed along the north wall in the upper valleys since the disappearance of the trunk glacier. In the other two valleys, Stepanek and Colorada, the bulk of the sediments is active, inactive, and fossil rock-glacier debris. Below about 2700 m, the topography is dominately that produced by running water on underlying gravels and tills. Both Vallecitos and Angostura Creeks are fed primarily by meltwater from winter precipitation and by melting ice from the small glaciers and rock glaciers in the upper parts of their valleys.

Relative Dating Methods

Since 1931, when Blackwelder demonstrated the value of comparing erosional modification of moraines and the weathering of granitic boulders at and just below the surface to distinguish glacial deposits of different stages in the mountains of western United States, some North American glacial geologists have relied on these techniques to work out morainal sequences. Blackwelder's criteria were refined by Sharp (1939), Richmond (1962), Birman (1964) and other students of alpine glacial deposits during the decades that followed. Most recently, a more comprehensive set of criteria has been worked out so that measurements of several features can be compared to establish the probable relative age of a particular drift and to correlate it from one valley to another (Birkeland, 1973; Carroll, 1974; Burke and Birkeland, 1979; Birkeland et al., 1979).

As soon as a moraine has been deposited, weathering and erosional processes begin to alter its surface. These surficial changes are progressive; thus deposits that have been exposed for a long time will be more greatly altered than those that have less exposure. Some subjectivity is present in the method, and the specific measurements of two or more workers are not always identical. Nevertheless, most geologists using these methods will be able to recognize the same stratigraphic units.

Use of such relative dating (RD) techniques in southern South America has been limited. Flint and Fidalgo (1964, 1969) examined the degree of weathering of granitic clasts in the soil profile to distinguish three tills in the region around Bariloche. They also used the height of outwash above present drainage and subjective evaluations of the degree of erosional modification of the landforms. They examined soil profiles but were unable to detect sufficient differences in the weakly developed profiles to use them for age differentiation.

Caviedes and Paskoff (1975) used differences in the degree of valley erosion since deglaciation, alteration of heavy minerals, and soil profile thickness to distinguish deposits of three glaciations in the Aconcagua and Elqui valleys of Chile. In the Lago Llanquihue area in Chile west of Bariloche, Argentina, Mercer (1976) used weathering and erosional modification of tills and the progressive thickness of the weathering rind on andesitic clasts to help identify six tills.

Wayne (1981) used many of the RD parameters used currently in North America alpine studies in working out late glacial-Holocene geomorphic history for the upper part of the Río Blanco basin. The RD methods found to be most useful in the examination of moraines and older diamictons in the Río Blanco basin were (a) morphologic changes, which included erosional dissection and thickness of loess; (b) weathering of surface and subsurface clasts; (c) soil profile development; (d) growth of lichens; and (e) cover of vascular plants.

In this report we wish to present additional data on the deposits in the basin of Río Blanco that we believe will firmly establish the glacial origin of the diamictons in that valley downstream from the outermost moraines of the last glaciation. In addition the stratigraphic sequence worked out through the use of multiple relative dating techniques will be presented, along with efforts to correlate the units with those of the Northern Hemisphere. Field work for this study was done during the period January to June 1980.

Glacial Geology

Introduction

The Cordón del Plata, along with other ranges in the dry Central Andes, supported larger glaciers than the present ones during the last major glaciation, the termination of which took place by 12,000 B.P. in Patagonia (Mercer, 1976, p. 155). Ice of this glaciation, named the Vallecitos Stage (Corte, 1957, p. 14), extended downvalley to about 2600 m, where it deposited end moraines across the valleys of both Vallecitos and Angostura Creeks.

Although geologists agree that glaciers expanded extensively in the valleys of the Mendoza Andes during the last glaciation (Vallecitos = Wisconsinan/Würm), the idea that glaciers were as large during earlier cold periods of the Pleistocene has been questioned. Dessanti (1946), Groeber (1954), and others described diamictons that they regarded to be of glacial origin in the valleys of Ríos Diamante and Atuel in the southern part of Mendoza Province. Corte (1957) described several exposures of a diamicton exposed in the steep valley walls of Río Blanco and traced from the junction of Q. de la Angostura and Q. de los Vallecitos to Potrerillos, where Río Blanco enters the valley of Río Mendoza. He considered this diamicton to be till deposited during an earlier glaciation.

In contrast Polanski (1963, 1965) regarded the diamictons described by Groeber and Corte to be volcanic mudflows that, along with the bouldery gravels that accompany them, represent the stratigraphic record of uplift of the Central Andes. Polanski argued that the region of 32° S lat. is and always has been too dry to have supported Pleistocene glaciers sufficiently large to have reached the piedmont, and he agreed with Stappenbeck (1917) that the most extensive glaciation of that part of the Andes was the last one.

Holocene deposits

Modern glaciers of the Cordón del Plata are typical of those of the dry Central Andes. They are small and their lower reaches are debris-covered. Many display a surface sequence from cirque headwall to terminus that includes glacier–covered glacier–thermokarst–structured debris–rock glacier (Corte, 1978). Most of the small glaciers expanded and shrank during Holocene time, and some show a record of three glacial advances (Wayne, 1981). The RD criteria used to distinguish the deposits of each Holocene advance are summarized in Table 1.

The youngest Holocene glacial advance, called Holocene III in this report, ended about a century ago, and the debris-covered ice margins have begun to melt back from their maximum positions, which were about 3600 m above sea level. In Q. de los Vallecitos, a large ice-cored moraine is now isolated from the main tongue and its flank is becoming rock-glacierized. In the other valleys, active and inactive-but-uncollapsed rock-glacier tongues as low as 3250 m in altitude are the stratigraphic evidence of Holocene III cold period.

Table I. Relative Dating (RD) characteristics of the Late Pleistocene and Holocene glacier and rock glacier deposits of the upper part of the Río Blanco drainage basin

Characteristics	*Vallecitos I*	*Vallecitos II*	*Holocene I*	*Holocene II*	*Holocene III ("Little Ice Age")*
Position of moraines or rock glaciers	end moraines low in valley (below 2600 m) outer lateral moraine smoothly rounded	moraines and fossil rock glaciers fill valleys between 2600 and 3400 m	rock glaciers at 3200 m	clustered moraines extend to 3450 m rock glacier tongue to 3100 m	ice-cored moraines beyond present ice margin active or recently inactive rock glaciers to 3250 m, fronts 33°–45°, contain ice
Modification of constructional landforms	loess variable, 35–80 cm moraines partly destroyed by stream	loess averages 20 cm; moraines trenched but little valley widening rock glacier fronts 23°–30°	loess averages 5 cm rock glacier front 25°–32° smoothly rounded	no loess trenched only where melt-water stream passes through; rock glacier fronts 27°–30°	ice-cored moraines starting to collapse some rock glaciers inactive. rounded crests, still contain ice
Boulder weathering[1]	granites etched, rounded, pitted to 3 cm quartzites subrounded: (A)0–(SA)57–{SR)43–(R)O	granites etched, rounded, pitted to 3 cm non-granitic rocks: (A)10-(SA)37–(SR)32–(R)21 rinds 0.5–1.0 mm	no granites; quartzites: (A)29–(SA)62-(SR)9–(R)0 rinds 0.5 mm on diorites	no granites; quartzites: (A)20–(SA)73–(SR)7–(R)0 rinds 0.2 mm on diorites	all angular
Soil profile development	moderate, Mollisols B–horizon massive to weak blocky structure 5 YR3/3-5/4(B)/10YR 4/4(C)	moderate. Mollisols B-horizon massive 7.5 YR4/4(B)/10YR4/4(C) 7.5YR4/4(C)	weak, Inceptisols. cox horizon loess/debris 7.5YR4/4 to 5YR4/4(B)/	weak, Inceptisols cox 0-5 cm (till) 10YR4/3(B) /2.5 Y5/2(C)	none, Entisols
Lichens	10-90% covered diameters meaningless; multigenerations	50-70% covered diameters meaningless	30-40% covered *R. geographicum* 70 mm	10-40% covered *R. geographicum* to 60mm	cover less than 2% no *R. geographicum* observed
Vegetation	fully covered (60-90%) grasses, forbs, woody shrubs	fully covered (60-90%) grasses, forbs, woody shrubs	about 40% covered grasses, forbs, prostrate *Adesmia*	5-20% covered grasses, forbs	less than 2% covered succulent forbs
Other features		large, massive moraines sorted stripes, lobes on slopes above moraines avalanche cones beside moraines in valleys	thick loess accumulation beneath boulders at toe of slope sorted circles 1-1.5 m diam. to 50 m downslope	sorted circles 1-1.5 m diam. on adjacent surfaces 750 m downslope	many rock glaciers expanding now ice-cored moraine rock-glacierized
Estimated age	>40.000 B.P.	19,000–13,000 B.P.	4600–4000 B.P.	2700–2000 B.P.	300 B.P.–0

1. A = a:ngular; SA = subangular; SR = subrounded; R = rounded

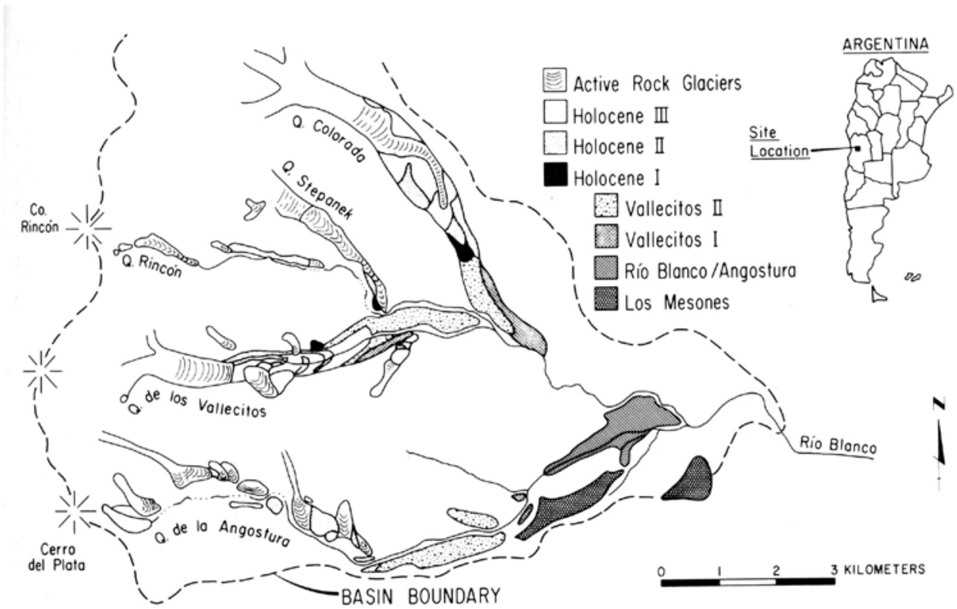

Fig. 2. Map of Quaternary deposits in the upper part of Río Blanco drainage basin.

The Holocene II glaciation was sufficiently intense that an ice margin advanced to about 3450 m in both Q. de los Vallecitos and Q. de la Angostura, where it deposited the outermost of a group of looping morainal ridges (Figs. 2 and 3). These small but distinctive moraines contrast with the valley-filling masses of till left by earlier and later debris-covered glaciers and suggest that the surface of the advancing ice may have been relatively clear. In the other large valley, Q. Colorada, a narrow rock glacier tongue extended almost to 3100 m along the left side of the valley, overriding the side margins of older rock glacier debris. No materials were found that would permit radiometric dating of this glacial advance, but extrapolation from RD data, including lichen cover, suggests correlation with the advance Mercer (1976) has dated at 2000 to 2700 yr B.P. Burrows (1979) summarized Southern Hemisphere climatic data, showing that glacial advances have been reported for several areas for the period 3000 to 1500 B.P. (1000 B.C. to A.D. 500) in Patagonia. After this glacial advance, the climate warmed sufficiently that the glacier disappeared completely from Q. de la Angostura, melted back well above the clear moraines in Q. de los Vallecitos, and caused collapse of the ice cores of the rock

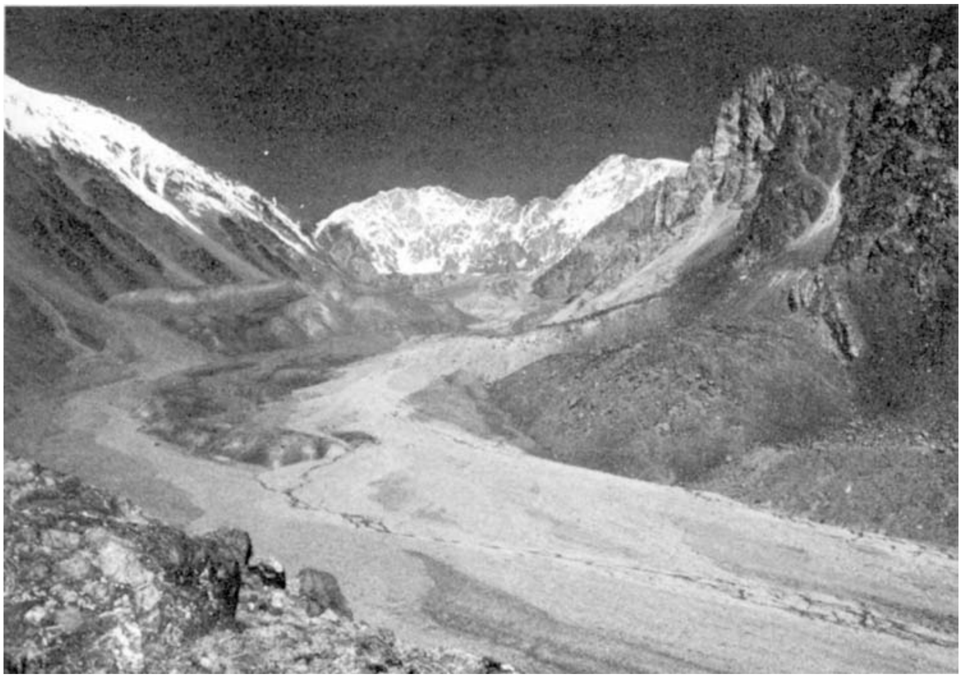

Fig. 3. Vallecitos II moraine and Holocene I, II, and III moraines and rock glaciers in Q. de los Vallecitos showing successive overlap above 3300 m.

glacier tongues in Q. Colorada. Europe is reported to have experienced unusual warmth for a few hundred years, from about A.D. 800 to A.D. 1200 (Lamb, 1965). Very possibly the Southern Hemisphere had a similar warm period after the Holocene II advance that melted glaciers extensively.

The oldest Holocene I deposits extend beyond those of the Holocene II period only in a few places (Fig. 2), and all recognized are fossil rock glaciers. A lobate rock glacier in Q. de los Vallecitos expanded over an older lateral moraine and was in turn overlapped by the outer lateral moraine of the Holocene II ice (Fig. 3). A single distinctive rock glacier ridge of the Holocene I glaciation lies outside the massive deposits of Holocene II activity in Q. Colorada, and a small rock glacier lobe with soil and boulder-weathering characteristics similar to the other deposits of this age protrudes from the base of the active frontal slope of the rock glacier in Q. Stepanek. Again, no organic material that would permit radiocarbon dating of this cold period was found, but we correlate it with the one Mercer (1976) recorded as having reached its culmination in Patagonia 4200 to 4600 years B.P.

Fig. 4. Morainal embankment in Q. de los Vallecitos.

Vallecitos Stage

Beyond the outermost Holocene moraines and fossil rock glaciers in each valley are massive and hummocky embankments of bouldery till (Fig. 4). Lateral moraines form ridges above and slightly outside of the main central morainic mass, and a small terminal ridge crosses each valley at an altitude of 2600 m to 2700 m. The outer lateral moraines lie within the sides of dissected U-shaped troughs that undoubtedly owe their dimensions and shape to erosion by an earlier and larger glacier tongue. Although nearly obscured by debris cones along the valley walls, a glacial trim line, marked by an abrupt change from ragged frost-riven upper slopes to smoother and steeper lower ones that are partly buried beneath scree can be seen along the sides of the valleys.

Three major valley glaciers, one of which had a large tributary, fed ice toward the junction of streams that make up Río Blanco. Lateral moraines along the valleys indicate that during their maximum advance, all probably were Alpine type glaciers. The terreplein-like deposit that fills each of the valleys suggests that they became debris-covered Andean-type glaciers (Polanski, 1954) during the late phase

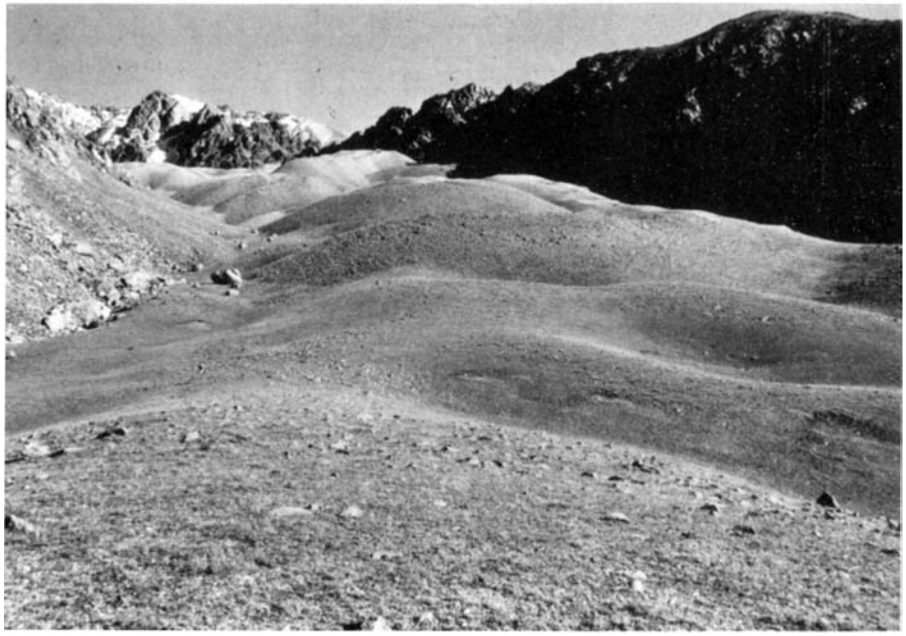

Fig. 5. Active rock glacier high in Q. Colorada; rounded crests and gentle slopes of Vallecitos-age fossil rock glacier in foreground.

of the glaciation, as the ice tongues shrank and finally receded into the cirques.

The surficial features of the till indicate that the distal parts of the glaciers in the two valleys that trend west–east probably were debris-covered but the central and proximal sections may have been relatively clean ice. Deposits are almost lacking in the upper parts of these valleys, so final melt back must have been more rapid than the rate of debris production from the quartzite slopes above the ice. In contrast, the ice in the valleys that trend southeastward became more heavily debris-covered from the highly shattered volcanic rocks that make up the slopes of its basin. The topographic form of the Vallecitos deposits in this valley, Quebrada Colorada, (also called Quebrada de las morrenas coloradas), is that of a muted rock glacier. The surface is one of ridges and pits very similar to that of the present active rock glacier higher in the valley, but with rounded crests and more gentle slopes (Fig. 5). No stream cuts through these deposits; rather, the meltwater from the small glaciers and the active ice-cored rock glacier filters through these older and highly permeable sediments to emerge as a spring below the fossil rock glacier deposits.

A large, broad morainal mass fills the central part of Q. de los Vallecitos. Lateral ridges stand above the central part of the moraine trenches but do not lie against the bedrock valley walls. Vallecitos Creek flows between the bedrock valley wall and the large left lateral moraine that fills most of the valley and in a few places has undercut it to expose the till. Both at the junction with Q. Stepanek and about 700 m downstream, stream-cut banks expose a second till beneath the thick surface till. Still farther downstream, where Q. de los Vallecitos and Q. Colorada join, the creek has cut a trench through the glacial deposits. Most of the high outcrop is brown (5YR5/6) rhyolitic debris of the Q. Colorada rock glaciers, but a lens of gray (2.5Y 4/4 to 10YR6/4) till from the quartzite-walled Q. de los Vallecitos in the deposit confirms the contemporaneity of deposition in the two valleys.

Both the till and the rock glacier deposit in the exposures are compact and probably were consolidated shortly after deposition by the weight of overriding ice and debris. Coarse clasts are sufficiently abundant that fine grained debris does not completely fill the interstices, although the rock glacier debris is much more open textured than are the tills. Striated bedrock surfaces were seen in a few places, but no striated cobbles or boulders were observed in any of the exposures of undisputed till. SEM (scanning electron microscope) examination shows that many of the quartz sand grains in both the tills and the rock glacier debris show clear evidence of having undergone glacial grinding (Fig. 6a, b).

The positions of moraines and trim lines, boulder weathering, loess thicknesses, and soil profiles provide evidence that during the Vallecitos Glaciation, the ice had at least two maxima. The main part of each valley between 2700 m and 3400 m contains deposits the surface of which is till deposited during the main phase of the glaciation (Vallecitos II). Mercer (1976, pp. 151–155) found that the Llanquihue ice at 41°S. in Chile reached a maximum position between 19,500 and 13,000 yr B.P., and that deglaciation was extensive by 12,000 B.P. The Vallecitos II tills in the Río Blanco basin undoubtedly are of the same age.

Outer lateral moraines and a low, hummocky, boulder-covered end moraine lie just beyond the main Vallecitos Stage moraines in each valley. These moraines have thicker loess cover, and surface boulders show a somewhat greater degree of weathering than do the massive Vallecitos II moraines (Table I). In contrast to the complete lack of B-horizon structure in the younger soil profiles, a weak blocky structure

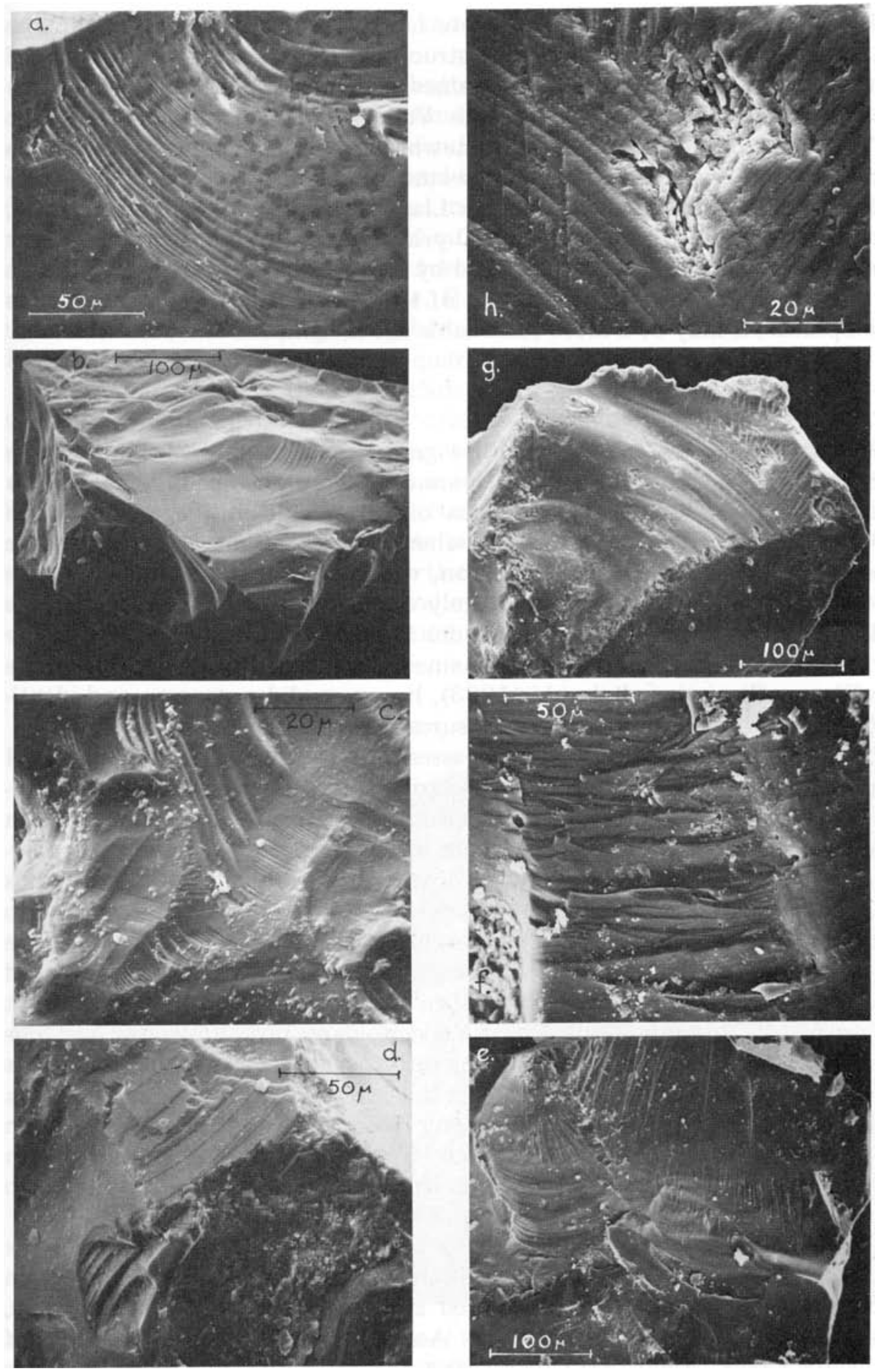

Fig. 6. Scanning Electron Microscope images of quartz grains from glacigenic deposits in Río Blanco basin: **a)** from Vallecitos II till, Q. de los Vallecitos; **b)** and **c)** Vallecitos II rock glacier, Q. Colorada; **d)** pre-Vallecitos II till, Q. de los Vallecitos; **e)** Río Blanco till, Q. de la Angostura; **f)** Angostura till, Q. de la Angostura; **g)** Los Mesones till, Meson del Plata; **h)** upper right part of **g** at greater magnification to bring out etching detail.

Table II. Relative Dating (RD) characteristics of the Pleistocene glacial deposits, Río Blanco drainage basin

Characteristics	*Los Mesones*	*Angostura*	*Río Blanco*	*Vallecitos I and II*
Position of constructional landforms	none left; till present along valley to 1800 m	none recognized; surface of till buried to about 1950	morainal remnants present about m 2200 m, 1900 m, and 1700 m till present in valley to 1400 m	moraines and fossil rock glaciers in valley between 2400 m and 3400 m
Modification	fragments of once sloping plain cap mesetas 75-200 m above present streams some loess in soil profile	buried beneath younger till between 25,00 m and about 1950m	pediment cut across till surface from 2500 to 2100 m: moraine at 1700 m deeply trenched coarse gravel over till downstream loess cap 15-30 cm	moraines fresh to rounded, outer ones moderately breached inner moraines trenched loess 20-35+ cm
Boulder weathering	few boulders visible on surface only quartzites, all well rounded, many split quartzites in soil completely weathered; few granites observed, all completely grusified; boulders exposed only along edges	no boulders at surface granites in buried paleosol grusified	surface boulders not common only quartzite fragments to 3 m in soil profile at outermost moraine recognized boulders on higher moraine fragment (A)15-{SA)21-(SR)25-(R)39% with 70% broken	granites rounded, etched, pitted to 3 cm quartzites subround to subangular rinds 0.5 to 1.0 mm V.I: (A)0--(SA)57–(SR)43-(R)0 V.II: (A)10--(SA)37-{SR)32--(R)21
Soil profile development	very strong; at 3000 m argillic B-horizon with strong blocky structure (27 cm thick) aridisol below 2350 m, with thick chalky Bca-Cca horizon locally strongly cemented (12-80+ cm)	buried paleosol with strongly developed argillic B_2 weak Bca and Cca horizons	moraine fragments at 1900 and 2300 m: Aridisol with Bca 25-35 cm and Cca(K) horizon 35~0 cm, platy outer moraine at 1700 m: silty aridisol, Bca 35~0 cm, weakly cemented	moderate, Mollisols B-horizon massive to weak blocky
Other features	grassland, with scattered woody shrubs rests on weathered andesite in Q. de la Angostura till calcareous where exposed	fills bottom of bedrock valley	capped by ash bed in a few exposures till not calcareous under pediment but contains secondary $CaCO_3$ in other places	grass with woody shrubs till not calcareous acid
Estimated age	1.2-1.0 × 10^6 yrs	450,000 yrs B.P. (?)	200,000–100,000 B.P. (?)	Wisconsinan/Würm

was observed in a few of the profiles examined on these older moraines, and they are redder, having a hue of 5YR compared to 7.5YR for the Vallecitos II soils (Table IIIA,B).

These characteristics indicate a somewhat greater age, and in the absence of datable materials in this area, it seems reasonable to correlate the early Vallecitos till (Vallecitos I) with earlier Llanquihue tills, which Mercer (1976, p. 148) found to be more than 40,000 years old. This is considerably greater than the age of 20,000 years suggested by Wayne (1981) for these Vallecitos I moraines, but in view of the nature of the loess cover and the soil profile development, it may be a more reasonable age assignment and correlation.

Table III. Descriptions of tills and characteristic soil profiles or paleosols

A. Vallecitos II till and soil profile	
Left lateral moraine of large morainal mass, Q. de los Vallecitos. At junction with Q. Colorada. Vegetation cover 100%, altitude 2950 m.	
0-10.cm	Loam, 10% clasts 2 mm, 7 .5YR 3/2, pH 6.4, base clear
10-22 cm	Loam, pebbly, 50% 2 mm, 7.5YR 3/4, pH 6.0, base clear
22-40 cm	Silt, sandy, pebbly, 50% clasts 2 mm, 10YR 4/4, loose, pH 6.0
B. Vallecitos I till and soil profile	
Crest of end moraine in offset gorge of Q. de la Angostura. Vegetation cover 90%, slope 5% to E, altitude 2570 m.	
0-11 cm	Loam, sandy, 5YR 3/2, s1. plastic, pH 5.0, base clear
11-26 cm	Loam, 5YR 5/3, s1. plastic, massive, pH 5.0-5.2, base clear
26-46 cm	Loam, sandy, pebbly, 50% clasts 2 mm, some large, 10YR 4/4, loose, pH 5.8-6.0
C. Río Blanco till and soil profile above Angostura till with buried paleosol	
Section exposed in stream bank along Q. de la Angostura, 1000 m above junction with Q. de los Vallecitos, altitude 2250 m.	
Rio Blanco till	
0-7 cm	Loam, 5YR 3/2, loose, roots abundant, pH 6.4, base diffuse
7-13 cm	Loam, 5YR 4/2, loose, pH 7.0, base abrupt
13-35 cm	Silt, 7.5YR 7/2, chalky, cementation weak to strong, strongly effervescent with HCl, base clear (stage IV carbonate development)
35-15.00 m	Till, pebbly, sandy, silty, 5Y 5/3, calcareous throughout
Disconformity	
Angostura till	
6.00-15.15 m	Loam, 10YR 4/4 mottled with 7.5YR 4/4, very compact, base clear
6.15-15.40 m	Loam, 7.5YR 4/6, very compact, base clear
6.40-6.83 m	Loam, 5YR 4/4 mottled with 5YR 3/3, clayey, weak blocky structure, pH 5.6, base clear
6.83-7.58 m	Loam, 7.5YR 5/4 with veinlets of 7.5YR 7/2. Contains ghost cobbles and grusified granitic boulders
7.58-8.20 m	Covered
8.20-11.20 m	Loam, silty, pebbly (till), 2.5Y 5/4, pH 6.2
11.20–	Covered

Río Blanco and Angostura Stages

Beds of diamicton—massive, olive gray (5YR5/2 to 6/2), boulder-rich sediment with a sand-silt matrix—are exposed along the channel of Río Blanco from the lowermost moraines of early Vallecitos age at 2600 to 2700 m downstream to Potrerillos, where the Río Blanco flows into the valley of Río Mendoza. This diamicton, which contains abundant quartzite and some rhyolitic boulders that surely come from the outcrops of these rocks above 3000 m in the Cordón del Plata, was regarded to be a till by Corte (1957), who described it and named the episode of its deposition the Río Blanco Glaciation. Polanski (1963), however, did not agree, and identified the same diamicton in these exposures as a mudflow deposit.

Exposures where Angostura Creek passes through the outermost Vallecitos I moraine at about 2600 m may help clarify this controversy. At the downstream edge of the moraine, Vallecitos till lies on dark reddish-brown weathered material, perhaps the remains of an older till, which, in turn, overlies weathered granite. About 100 m downstream, the valley widens and its floor is a boulder-strewn surface through which trenches 1 m to 3 m deep anastamose. The abundant boulders on the surface are rounded and most are fresh, although the surfaces of the scattered granite clasts are fully etched and some show slight pitting. The entire valley floor is covered with about 30 cm of silt, undoubtedly loess of Vallecitos and post Vallecitos age. The soil profile observed in several pits dug into the surface and in the exposures along the bank of Angostura Creek is in this loess; an underlying diamicton is virtually unaltered. The B horizon is about 15 cm thick, is dark reddish brown (5YR3/3) and moderately acid (pH 5.6–5.8). Generally it is massive, but in one pit showed weak blocky structure. In most respects, the soil is similar to those observed on the Vallecitos I moraines (Table III).

The nearly vertical, 8 m high banks of the channel of Angostura Creek through the current-swept segment of the valley expose two diamictons in some places separated by a weathered zone developed on the lower one, almost continuously for nearly 3 km. Across the valley from the mouth of Vallecitos Creek, Angostura Creek swings against its valley wall and exposes an unusually complete section of these two layers and the paleosol on the lower one (Fig. 7 and Table IIIC).

Fig. 7. Exposure along Q. de la Angostura of Río Blanco and Angostura tills, with strongly developed buried paleosol at top of Angostura till.

The two diamictons that fill the bottom of Angostura valley are calcareous, otherwise they are lithologically similar to the tills of the Vallecitos Stage exposed upstream. They have a sand-silt matrix with a large number of coarse clasts (Table II). Single-crystal quartz grains are by no means rare in the samples of these diamictons, but most of the sand-sized particles are fragments of quartzite. SEM images of quartz sand grains from samples of both diamictons in this section have fractured surfaces that show clearly they have undergone glacial transport (Fig. 6e, f). Fractured grains are fresh in both of these diamictons, but pits, probably from solutional etching (Krinsley and Doomkamp, 1973) can be seen in quartz grains from the lower bed.

Although it is likely that the debris of a mudflow would contain glacially transported grains if the mudflow originated in a melting glacier, it is much more likely that these diamictons, at this place in the Río Blanco valley, were deposited directly by glacial ice. Although no striated cobbles or boulders were noticed in the diamicton along Angostura Creek, one must be aware that most of the large clasts in these sediments are quartzite, which striates with difficulty, so much

Fig. 8. Dated bed of volcanic ash between Río Blanco till below and a coarse gravel exposed along Río Blanco valley 6 km east of Cordón del Plata.

so that no striated boulders were seen in the unquestioned tills higher in the valley. In addition to the possible glacial origin of the diamicton, one additional feature of the Vallecitos, Stepanek, and Colorada valleys suggests that they have been occupied by glacial ice at least once prior to the Vallecitos glaciations. The Vallecitos II lateral moraines do not lie against the walls of those valleys, the lower parts of which show dear evidence of having been shaped by moving ice, and Vallecitos I moraines reach only slightly farther, so the glacier that eroded the valleys must have been larger than the one of Vallecitos age. Avalanche troughs cut the ice-scoured valley sides, though, and debris cones fill parts of the valleys outside the lateral moraines. At least one of the ice tongues that enlarged the valleys and shaped the valley sides undoubtedly was large enough to have extended beyond the outer moraines of Vallecitos age.

Two pre-Vallecitos tills are present along the Angostura valley and can be seen in at least one place in the “Narrows” of Río Blanco, yet only one is present in any exposure along the banks of Río Blanco after it leaves the cordillera. The lower till is more boulder-rich than the upper in the exposures where the two can be seen in superposition. In most of the downstream exposures examined, both size and abundance of boulders resemble those of the upper till.

About 6 km east of the margin of the Cordón del Plata, in nearly every exposure for a few hundred meters, a bed of volcanic ash separates a till from coarse gravels that overlie it (Fig. 8). Efforts to date the ash by the zircon fission-track method were only partly successful. Charles Naeser and Glen Izett, U.S. Geological Survey, Denver reported (pers. comm., 1980) that it probably is between 100,000 and 200,000 yr old, but too young to date more precisely by the method. This date, coupled with the lithic similarity with the upper till exposed near the junction of Angostura and Vallecitos Creeks and the degree of development of the paleosol on the lower till combine to indicate that the till that extends to Potrerillos along the Río Blanco valley is the upper one. This till, then, is the one named the Río Blanco till by Corte (1957). Correlation with other areas in the absence of radiogenic dates is not simple, but, based on the soil profile and the ash date, it seems reasonable to correlate the Río Blanco till with the Guardia Vieja Glaciation of the Aconcagua Valley (Caviedes and Paskoff, 1975).

The lower till exposed along Angostura Creek can be traced through the narrows of Río Blanco, but has not been recognized beyond the east edge of the Cordon del Plata. Because of the extent of its exposure along Angostura Creek, we are naming it the Angostura till and the glacial advance that deposited it the Angostura Glaciation. The nature and thickness of the soil profile that was developed on it prior to its burial indicates that conditions at 2200 m in the Río Blanco basin were relatively humid and that considerable time—probably measured in many tens of thousands of years—elapsed before it was buried. It may correlate with the Salto de Soldado drift of the Aconcagua Valley in Chile, the soil profiles on which were reported to be highly weathered (Caviedes and Paskoff, 1975).

Los Mesones Stage

Angostura Creek has an open valley both above and below the narrow part where the lower part is offset to the north. An elongate mesa that stands more than 100 m above the present channel continues along the alignment of the upper valley where the offset starts. The grass-covered surface of the mesa is smooth, and it is underlain by a bouldery diamicton. Since deposition, the topography has become inverted.

The diamicton that caps the mesa is 12 m thick, but is not well exposed. Weathered boulders stand above the surface along the sides of the deposit. Most of the boulders are quartzite, but a few volcanic and plutonic rocks are present. Two granite boulders observed were totally grusified, and a rounded andesite boulder displayed a 15 mm thick weathering rind. A quartz vein through one of the exposed quartzite boulders stands 8 cm in relief.

Near the east end, the soil has a thick cemented carbonate horizon 12 to 75 cm thick, in which pedogenic $CaCo_3$ makes up about 60% of the volume. At the west end of the same surface, though, only 2500 m away and about 100 m higher in altitude, a 25 cm thick reddish brown (5YR 4/3) blocky horizon is buried beneath loess and some mass-wasted debris. Even though greatly different soil-forming processes have affected this surface, both are well developed and clearly represent considerable time for their formation.

A short distance east of the frontal slopes of the Cordón del Plata, a second flat-surfaced ridge stands above the south side of the Río Blanco valley. This ridge, the Meson del Plata, is 3000 m long and 500 m across. Boulders cover its surface, and in a few places erosion has exposed a cap of greenish gray diamicton that overlies steeply dipping sandstones of Tertiary age. Most of the boulders exposed on the surface and edges of the Meson del Plata are quartzite and are extensively split, and two deeply rotted granite boulders were observed. Most of the sand grains recovered from a sample of the compact matrix collected near the base of the diamicton at an exposure at the east end of the Meson del Plata are lithic fragments of quartzite, but more than a third are authigenic gypsum. Quartz grains in a sample show fracture surfaces that are characteristic of glacial transport, although the surfaces have been etched and pitted (Fig. 6g, h), indicative of the long time they have been affected by vadose groundwater since deposition. Because of this, as well as its thickness and boulder content, this diamicton probably also is till. Its position above present drainage suggests that it is the same till as that discussed earlier.

The soil profile and the diagenetic changes observed on the quartz grains as well as the dissection that has taken place since its deposition indicate considerable age for this diamicton; for it we are keeping the name applied by Polanski (1963), Los Mesones. At this time it seems reasonable to suggest that it may correlate with the glaciation in Patagonia that Mercer (1976) said was the most extensive, and which he dated as having been deposited between 1.2 and 1.0×10^6 years ago.

Paleosols and Paleoclimates

The degree of soil profile development provides a useful criterion to distinguish the relative ages of two or more geomorphically stable surfaces that are underlain by similar materials. To give them absolute ages, however, is much more difficult. The characteristics of the soil profiles also reflect the dominant climatic and vegetational conditions under which they developed. If soils on comparable parent materials exhibit distinctly different morphologic features, the climatic conditions under which they formed may have been dissimilar, and these features can be used to infer past climatic conditions (Birkeland, 1974). Vallentine and Dalrymple (1976) point out that modern soils and the environmental conditions that formed them are still not well enough understood, however, to permit extrapolation of past climates based solely on soil characteristics with a high degree of confidence.

Soil profiles on till of the Vallecitos II Glaciation are thin, dark brown (7.5YR 4/4), acid, and moderately weak (Table III, A). The A horizon is dark and high in organic matter; although the soils contain clays, they lack a structural B horizon and so are Inceptisols. Soils on Vallecitos I tills are similar but somewhat thicker (Table III, B). Conditions during the past 13,000–20,000 yr varied from cool and moist to warmer and drier, followed by the fluctuations that accompanied three brief Holocene glaciations (Wayne, 1981). These soils carry the dominant climatic imprint of that period.

In contrast, the soil profile observed on the *Río* Blanco till, where it is present in the same area and altitude as the lower part of the Vallecitos tills, is an Aridisol. A platy Bca horizon about 30 cm thick lies beneath 15 to 30 cm of dark reddish gray (5YR 4/2) silt loam (Table III, C). Such a carbonate-rich B horizon could not have developed under the conditions that have prevailed since the Vallecitos Glaciation, and so it probably is not in equilibrium with the present climate (Stephens, 1965). The parent material beneath the solum is calcareous throughout, but most of the carbonate seems to be secondary. No carbonate rocks exist higher in the valleys, and a sample of sand from this till contains secondary $CaCO_3$ grains. The till is not calcareous in exposures that probably were below the water table until post-Vallecitos incision of Angostura Creek. Therefore, the Ca ions in the soil profile had to be derived from the weathering of quartzitic and rhyolitic clasts, or airfall Ca in precipitation. Surfaces of Vallecitos age have a loess cap 15 to 30 cm or more thick, so comparable accumulations must have settled on older surfaces. The secondary $CaCO_3$ could be the result of weathering of aeolian silt and an arid climate that must have prevailed during much of the time since the till was deposited.

All soil profiles on the Angostura till are buried paleosols that formed during the time between disappearance of the Angostura ice and burial of the weathered deposit beneath the Río Blanco till. The buried profiles are vastly different from the Aridisols that cap the Río Blanco till. Some organic matter is present where the paleosol was in the stream floor, but it has been oxidized or scraped away from the surface of the most complete paleosol exposed (Table III, C). All of the exposures show the paleosol to have a thick argillic B2t horizon that is brown (7.5YR 4/4), has a blocky structure, and is not calcareous. The structure and the absence of $CaCO_3$ in the B horizon are strongly indicative that the region received much greater moisture than that prevailing during the post-Río Blanco glaciation. The color could represent either warm conditions, considerable time, or both (Birkeland, 1974, p. 167). The thickness of the solum suggests that considerable time elapsed before it was buried.

The soil profiles on Los Mesones Stage till have strongly developed sola. From one end to the other of the 3 km long meseta that extends eastward from the upper segment of Q. de la Angostura (Fig. 2), the soils change from argillic to calcic. At the west end of the Meseta and at an altitude of about 2700 m, 25 cm of loess and 15 cm of small rock fragments have buried a paleosol with a 27 cm thick B2t horizon that is reddish brown (5YR 4/3), strong blocky with 4 mm peds, and acidic (pH 4.8). Such a paleosol surely developed for a long time under moist conditions.

At the east or downstream end of the same meseta at an altitude of about 2300 m, a soil pit dug into a nearly level, grass-covered surface revealed a completely different soil profile. The A horizon is dark brown (7.5YR 3/3); beneath it the B horizon extends from 5 to 12 cm below the surface, dark reddish brown (5YR 3/3), and has weak blocky structure. From 12 cm through 81 cm, where digging stopped at a large boulder, secondary $CaCO_3$ was abundant. From 22 to 75 cm, the top third of which was strongly cemented Stage IV of carbonate buildup (Birkeland, 1974), pedogenic lime made up more than 50% of the soil volume. The dominant conditions at the place where such a strongly developed Aridisol formed must have been dry and warm for a long time for the strength of the profile to resist the changes caused by more cool and moist climatic conditions that accompanied the later Pleistocene glaciations.

Correlation

Correlation of the glacial deposits of the Cordón del Plata in the dry Central Andes with those of another continent is fraught with uncertainties, not the least of which is that we cannot be sure that each of the glaciations was synchronous world wide. A second major source of uncertainty arises from interpretation of the marine oxygen isotope record, which contains many more cold-warm cycles that we have been able to recognize on the continents. One seldom-expressed possibility is that all the major isotope cold periods correspond with the growth of ice sheets on the northern continents but that most of the glaciations were so much less extensive than those recognized that their deposits have been destroyed or obscured.

No radiocarbon dates are available, but there is little reason to assume that the Vallecitos II Stage in the dry Central Andes might have lasted longer than the Llanquihue Glaciation in Patagonia, which had terminated by 13,000 yr B.P. (Mercer, 1976). All evidence in the Cordón del Plata points to a rapid disappearance of the glaciers after they had melted back above 3300 m. The Vallecitos Stage thus would have been contemporaneous with the Würm of the Alpine sequence and the Wisconsinan/Pinedale of North America. Vallecitos II surely correlates with marine oxygen isotope stage 2 (cold). Vallecitos I may represent the cold period marked by isotope stage 4a (Shackleton and Opdyke, 1973,1976; Berggren et al., 1980).

Deposition of Río Blanco till was followed by a warm and dry period of sufficient duration to produce a strongly developed soil carbonate zone. The till also is overlain by an ash bed dated as between

100,000 and 200,000 yr old. Marine oxygen isotope stage 6 was calculated by Shackleton and Opdyke (1976) as 195,000–128,000 yr ago. Such a date fits the age of the ash bed, and stage 6 was long—perhaps long enough to have permitted growth of larger glaciers than those of the Vallecitos Glaciation. Isotope stage 6 also corresponds to the Illinoian Stage of the North American ice sheet and the Bull Lake of the Rocky Mountains (Pierce et al., 1976), both of which were more extensive in some areas than the younger Wisconsinan/Pinedale glaciers.

The Angostura Stage till fills the bottom of the lower valley of Angostura Creek, so it was deposited after the last major uplift of the range. It was in place long enough after deposition for a strong soil profile to develop before it was buried. Any statement as to the length of time needed to form that soil would be speculative, but a guess of at least 200,000 years is based on comparison with post-Lamoille soils in the Ruby-East Humboldt Range of Nevada and may not be too unreasonable. Oxygen Isotope stage 12, which is centered about 450,000 yr ago, was a cold period of considerable duration that took place long enough before Isotope Stage 6 to permit the Angostura–Río Blanco soil profile to form. The length and intensity of Isotope Stage 12 might also have allowed time for development of a glacier extensive enough to have deposited the Angostura till.

There is little agreement yet on which isotope stages correlate with the early Pleistocene glaciations recognized in North America and Europe. None of the glaciations of the Northern Hemisphere is considered to be of this age, although the youngest till in the "Nebraskan–Kansan" complex of the midwestern part of the United States, may be a possible correlative (Easterbrook and Boellstorff, 1980).

Sufficient time has elapsed since deposition of the Los Mesones till for Río Blanco to erode deeply below the remnants of the till. In those places that have remained geomorphically stable, a thick, strongly developed soil profile is present. Little else is available to suggest what the age of the deposit might be. Mercer (1976) states that the "greatest glaciation" in Patagonia took place between 1.2 and 1.0 m.y. ago. In the absence of any more positive means to date the Los Mesones till, it would seem reasonable to correlate it with the tills of the greatest glaciation of Patagonia.

The oxygen isotope stage sequence has been carried only as far as about 9 m.y. ago in the cores from the Pacific (Shackleton and Opdyke, 1976), although Van Donk (1976) extended the number sequence much farther back based on a core from the North Atlantic. Fluctuations of the oxygen isotope ratios for the period prior to the Jaramillo magnetic event are more difficult to interpret than the post-Jaramillo changes (Shackleton and Opdyke, 1976). Nevertheless, a major cold period appears in both the Pacific and Atlantic cores in the period estimated as between about 1.21 and 1.11 m.y. ago.

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