Quaternary of Chile: The State of Research

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Received July 16, 1976

The aim of this paper is to present a summary of current knowledge about Quaternary climatic changes, sea level fluctuations, tectonic deformation, and volcanic activity in Chile. In the Andean highlands of the hyperarid desert, glaciers and lakes fluctuated repeatedly. Evidence of pluvial periods is not well documented in the marginal desert. On the contrary, pronounced climatic changes are recorded in semiarid Chile. In central Chile two or three major glacial advances have been identified, but they remained confined within the high Cordillera. In the longitudinal Valley of the Lake Region geomorphic remnants of four glaciations have been described; ^{14}C dates are available for the last glaciation. The glacial history of the Fjord Region is still obscure. Whether Pleistocene climatic changes in the northern and southern part of Chile were synchronous or not is a problem which requires further investigation. Sea level fluctuations along the Chilean coast are in part ascribed to glacio-eustatic effects. They left striking sets of step like marine terraces in northern and central Chile. From a paleontologic point of view the Pleistocene corresponds to a pronounced move toward isolation and endemic development of the marine fauna. The Quaternary tectonic tendency seems to be toward extension and not compression expected as sea-floor spreading compensation. Normal faults limiting uplifted, downwarped, and tilted blocks are common. Folds are rarely found. Northern Chile is characterized by an imposing chain of about 600 stratovolcanoes. They rest on Tertiary ignimbrites which cover the *altiplano*. Quartz-bearing latite-andesites are predominant. Present volcanic activity is sporadic and weak. South of a conspicuous gap between 27 and 33°S, Quaternary volcanism reappears in the high Cordillera, and many volcanoes have erupted violently within historic times. Rocks are fundamentally andesite or basaltic andesite. Poorly sorted ashes including pumice clasts in the Central Valley south of Santiago are interpreted as volcanic mudflows of late Pleistocene age.

INTRODUCTION

The first major synthesis of Quaternary environments in Chile was written by Brüggen in his *Fundamentos de la geología de Chile* (1950) which is a fairly pioneering work. Other interesting publications in this field are the *Lexique stratigraphique international* (Hoffstetter *et al.*, 1957), Segerstrom's brief outline (1964a), and Miller's recent geological bibliography (1973). Because the last 10 years were a fruitful period marked by important contributions, the aim of the present paper, which improves and brings up to date a former attempt (Paskoff, 1971a), is to present and to try to evaluate our current knowledge about Quaternary conditions in Chile. Climatic changes, sea-level oscillations, tectonic movements, and volcanic activity will be successively examined.

CLIMATIC CHANGES

Because the Chilean territory is elongated, climatic changes which occurred during Quaternary time have to be studied according to latitude. From this point of view six main regions can be distinguished: the hyperarid desert, the marginal desert, semiarid Chile, central Chile, the Lake Region including Chiloé Island, and the Fjord Region. Among former publications dealing with climatic changes in Chile, those of Mortensen (1928), Caldenius (1932), and Brüggen (1929, 1946) are the most relevant.

The Hyperarid Desert (18–27° S)

Evidence of past glaciations has been reported in the high Andes of the Tarapacá and Antofagasta provinces. Katsui and Gonzales (1968) described small cirques and short U-shaped valleys, more or less obliterated by Holocene ash and lava flows, in the Nevados de Payachata Volcanoes (18° 10' S), which are above 6000 m (Parinacota 6350 m; Pomerape 6250 m). Here Pleistocene morainic deposits are noticeable at about 4500 m, although small sheets of ice are found today only above 5500 m. Similar observations were made by Engalbert (1958) on Sajama Volcano (6538 m) which lies at the same latitude as the Nevados de Payachata, but on the Bolivian side of the boundary; during the last glaciation small tongues extended down to 4500 m and left well-preserved lateral moraines. Thomas (1967) found cirques and glaciated valleys in the Cerro Yarvicoya mountainous area which stands on the western edge of the *altiplano*, at about 20° S lat; he mapped a conspicuous terminal moraine at about 4000 m in an unnamed tributary of the Quebrada Picuntiesa. In the same area but on the *altiplano* itself, near the Salar de Huasco closed basin, Tricart (1969–1970) distinguished two generations of Pleistocene moraines in the upper course of the Quebrada Sillillica: an old, weathered, 30–40 m high terminal moraine was built up at 4200 m by coalescent tongues of ice which flowed down from nearby volcanoes reaching almost 5000 m; another sequence of topographically less marked but fresher end moraines was left by small glaciers at about 4280 m. Each glacial advance coincided with a higher shoreline in the salar, at 30 and 15–18 m, respectively, above the present one, as previously observed by Brüggen (1950). These field observations and others (Vita-Finzi, 1959) which indicate more rainy climates at least twice, do not support Troll's opinion (1928) that the former perennial lakes of the *altiplano* were contemporaneous with the interglacial periods. The largest and the deepest of these lakes was probably an arm of Lago Minchin (20° S lat) which extended chiefly in Bolivia and which is estimated to have attained at its greatest extent a depth of more than 120 m, an area of about 25,000 km², and a length of about 480 km (Stoertz and Ericksen, 1974).

Farther south, in Antofagasta province, ice also left its traces (Francis *et al.*, 1974). Hollingworth and Guest (1967) mapped glacial forms between Toconce Volcano (22° 10' S) and the El Tatio geyser area, near the great Salar of Atacama. Slopes of Pleistocene strato-volcanoes show a topography characterized by cirques and U-shaped valleys. The largest glacier was about 10 km long, extending down to 4280 m, and it built up a conspicuous end moraine. Around the salar, lacustrine terraces, which indicate the existence at one time of a lake 30 m deep, were identified by Brüggen (1950). At a similar latitude, near the Bolivian border, 24 terraces and old deltaic deposits are clearly recognizable around the eastern end of the Salar de Tara (Stoertz and Ericksen, 1974).

At the time of the extension of glaciers and lakes in the Andean highlands of northern Chile, streams running down from them formed thick coalescent alluvial fans in the eastern part of the central valley, here named Pampa del Tamarugal. In the Arica area (Dollfus and Tricart, 1967) and in the Pampa so properly called (Tricart, 1966; Lecarpentier, 1973), four or five generations of alluvial deposits were laid down, each one corresponding to a climatically induced period of accelerated erosion in the Andes. In the northern part of Tarapacá province, near the Peruvian border, the existence of cool, shallow Quaternary lakes is evidenced by diatoms (Dingman and Lohman, 1963). Farther south and in the northern part of the Antofagasta province, the Central Valley once was occupied by a large lake known as Gran Lago Soledad, which, at its highest level, apparently attained a depth as great as 75 m and overflowed a divide in the Coastal Range, initiating the downcutting of the Rio Loa (Brüggen, 1950).

Pluvial periods also took place in the Coastal Range. They account for the building up of large alluvial fans, on regressive marine deposits at the foot of the steep littoral cliff, by *quebradas* (ephemeral streams) running down through deep canyons. These fans are no longer active: they have been dissected by continental runoff which excavated deep outflow channels and by transgressive marine action (Paskoff, 1973a).

The occurrence of more rainy—of glacial type in the Andean highlands and of pluvial type elsewhere—than at present in northernmost Chile is supported by paleontological findings (Casamiquela, 1969–1970), which indicate that large vertebrates (*Megatherium, Scelidodon, Macrauchenia, Equus*) coming from the Tarija region in Bolivia, lived in what is now hyperarid desert. Pleistocene climatic changes which appear to correspond to epochs of eustatic regression along the coast (Tricart *et al.*, 1969) seem to be related to repeated modifications of the atmospheric circulation. A displacement, and especially a weakening of the South Pacific Anticyclone, may account for easier arrival of the equatorial air mass, in other words for an *invierno boliviano* more vigorous and more far reaching than today. According to Tricart (1963) a decrease of the cold upwelling phenomenon affecting the Humboldt current may also explain an increase of rainfall in the Coastal Range. Here the last pluvial period began more recently than 37,200 ± 1600 years BP, the age of a regressive marine deposit underlying a dissected alluvial fan which has been largely destroyed by waves during the Holocene transgression (Paskoff, 1973a).

The Marginal Desert (27–30° S)

Here evidence of climatic changes during Quaternary time is not well documented. In the middle and lower course of the Río Copiapó (27° 20′ S), remnants of four alluvial terraces are found which, according to Tricart (1965), are climatically controlled. This opinion is not shared by Mortimer (1969, 1973) who was unable to discover evidence of glaciation in the Andean Cordillera, at least in the [illegible] the Salar de Mari[illegible] and the [illegible] Verde. Segerstrom (1964b), [illegible] typical rock glaciers, some several [illegible] in the Darwin Cord[illegible] (27° 45′ S) on the western slope of the cerro Cadillal (5300 m). They originate in cirque-like source areas, are bordered by lateral ridges as much as 10 m high, and may represent a senile stage of former clean ice glaciers. At any rate, it appears that marks left by climatic changes are very light in this part of Chile. Here the Andean highlands are especially arid today because neither the above-mentioned *invierno boliviano* nor the polar front rainy depressions reach them. They lie beyond the two main pluviometric systems found in Chile and such a geographic situation may explain why, during Quaternary time, climatic changes were particularly weak. Further investigations are needed to test this working hypothesis.

Semiarid Chile (30–33° S)

Recent and detailed field observations (Paskoff, 1970) point to pronounced climatic changes in semiarid Chile during Quaternary time. Because of its transitional position between the true desert and the rainy temperate region farther south, this part of Chile has been particularly prone to these changes due to latitudinal variations of the atmospheric circulation. Repeatedly, what is now semiarid Chile was a part of the rainy province during the cool humid periods of the Quaternary, characterized by a northward shift of about 5–6° latitude of the austral polar front.

The high Andes whose summits rise up to more than 4000 m were largely ice covered on several occasions during the Pleistocene. For instance, the Elqui Cordillera, near the Argentine border (Table 1) (30° S), in which only one small hanging residual glacier and névé patches are found today, displays a widespread and distinctive glacial modeling (cirques, U-shaped valleys several kilometers long), thus indicating powerful ice-stream erosion. At about 3000 m in the upper course of the Río Elqui, called Río La Laguna, the last (Laguna) glaciation left a well-preserved end moraine composed of fresh, loose till. Unfortunately, no material suitable for ^{14}C dating was found in it. At

TABLE I

GLACIAL ADVANCES IN THE ANDES OF CHILE BETWEEN 30 AND 42° S[a]

	Glacial advances limited to the High Cordillera				
	Elqui Valley 30° S (Paskoff, 1970)	Aconcagua Valley 33° S (Caviedes, 1972a)	Maipo Valley 33°30' S (Borde, 1966)	Cachapoal Valley 34°30' S (Santana, 1967)	La Laja Valley 38° S (Habbe, 1969)
Post glacial	Maximum extension of rock glaciers	Minor glacial advances at Portillo	Lo Valdés	La Isla Maitenes	
Last glaciation	La Laguna 3100 m	Portillo 2800 m	Los Queltehues 1700 m	El Manzanar 1200 m	"Talmorane" Quilleco
Penultimate glaciation	Tapado 2500 m	Guardia Vieja 1600 m	San Alfonso 1100–1200 m		"Hohenmorane" Las Lomas de Tucapel
Pre-penultimate glaciation II		Salto del Soldado 1300 m			"Aussenmorane" Río Huepil
Pre-penultimate glaciation I					
	Glacial advances reaching the Central Valley Lake District 39–42° S				
	Laugenie, 1971	Weischet, 1964	Illies, 1960	Lauer, 1968	Mercer, 1976
Last glaciation	Morainic loops at Lagos Villarica, Calafquen, Panguipulli, and Riñihue	Morainic loops at Lago Puyehue (*El Salto*)	Morainic loops at Lagos Panguipulli, Riñihue, and Ranco	Morainic loops at Lago Ranco	Morainic loops at Lago Llanquihue (*Llanquihue*)
Penultimate glaciation	Hualapulli (L. Villarica) Huidif (L. Riñihue)	*Río Negro II* *Río Negro I*	San José Antilhue	San Pablo Paillaco	*Casma* *Colegual*
Pre-penultimate glaciation II	San José (L. Villarica) Nochaco (L. Riñihue)	*Rahue*	Eastern slopes of the Coastal Range	Eastern slopes of the Coastal Range	*Río Frío*
Pre-penultimate glaciation I		*Contaco*			

[a] From Caviedes and Paskoff, 1973, modified. Correlations are fairly good for the last glaciation, only tentative for the penultimate glaciation, and highly speculative for older glaciations.

2500 m another terminal accumulation of weathered boulder clays indicates an older (Tapado) glaciation. In the Río Claro valley, a tributary of the Río Elqui, two different deposits of poorly sorted and poorly stratified sediments are noticeable, one at 1700 m, the other at 1500 m. Weischet (1969) assumed they were left by two separate ancient glaciations, older than the Tapado; nevertheless, this interpretation seems debatable, and a mudflow origin appears more appealing.

At the same time as glacial advances were occurring in the high Cordillera, the lower mountains (the Central Valley, typical of the Chilean physiography, is lacking here), which stand to the west with summits ranging between 2000 and 1000 m, were affected by a fall in the average temperature and especially by an increase in precipitation which led to nival and pluvial morphoclimatic conditions, because the lower relief features prevented permanent ice formation. Slopes were covered by layered periglacial screes, and very active torrential processes took place. Alluvial fans built up during the last nivo-pluvial period are no longer active today and are deeply cut by periodic floods. The setting of different generations of alluvial fans, one constructed within another, indicates a recurrent alternation of cool humid phases (construction of fans) and arid periods (destruction of fans).

Along the Pacific seashore where striking coastal terraces are found, pluvial periods, which apparently correspond to glacio-eustatic regressions, allowed a northward migration of the Valdivian rain forest as far as 30° 15′ S, as suggested by relict vegetation found at Fray Jorge. Some authors (i.e., Kummerow, Matte, and Schlegel, 1961), however, assume that the Fray Jorge cloud forest may instead represent the remains of the Cenozoic neotropical flora which covered a great part of South America before the important climatic differentiations that took place during the Pliocene. Nevertheless, the occurrence on coastal terraces of clayey red paleosols, containing not only montmorillonite but also kaolinite (Birot, 1970), supports the opinion of the scientists who think that Fray Jorge cloud forest is proof of the northward displacement of the Valdivian rain forest during a Quaternary pluvial period. On the contrary, during the more arid periods, before the glacio-eustatic transgressions were over, eolian deflation on sandy, emergent platforms built up thick dunes near the coastline. Several generations of dunes, each one separated from the other by red paleosols, have been described (Fuenzalida, 1956). Paleontological findings (*Macrauchenia, Hippidion*) also support such marked climatic changes (Hoffstetter and Paskoff, 1966) which recurred several times.

Central Chile (33–39° S)

In the upper Río Aconcagua valley (32° 50′ S) where, according to Lliboutry (1956), alpine glaciers descend to approximately 3000–3400 m, three major glacial advances have been identified in a detailed geomorphic survey by Caviedes (1972a). Each one left a distinct morainic system: near Portillo, at about 2800 m, huge lateral moraines and a sizable bouldery end moraine were deposited by two oscillations of the last (Portillo) glaciation; downstream from Portillo, at Guardia Vieja (1600 m) a broad arcuate wall is a weathered terminal moraine (Guardia Vieja glaciation); at Salto del Soldado (1300 m), highly altered moranic material behind a rock barrier of *verrou* type records the oldest reliably recognizable glaciation (Salto del Soldado glaciation). Regarding the Río Maipo valley (33° 43′ S), Borde (1966) thinks that two major glacial advances occurred. The first one (San Alfonso phase) deposited till at about 1100–1200 m. During the second one (Los Queltehues phase) an ice tongue reached 1700 m. The large Laguna moraine, at 2700 m, may represent only a temporary stillstand in the course of the last glacial recession (Marangunic and Thiele, 1971). Inactive rock glaciers found in the highest branches of the Río Maipo are ascribed to a brief late-glacial readvance (Lo Valdés phase). In the valley of the Río Mapocho, which joins the Río Maipo just after passing through the Chilean capital, Santiago, Tricart's observations (Tricart *et al.*, 1965; Börgel, 1969) are in good accordance with those of Borde since he also identified two generations of morainic deposits, the first one near La Ermita, at 1300 m, in the form of a weathered end moraine covered by periglacial colluvium, the second one visible near Corral Quemado, at 1500 m, but reduced to scattered remnants of dissected lateral and ground moraines. Finally, in the upper course of the Río Cachapoal valley (34° 10′ S) Santana (1967, 1973) described the glacial modeling left by an ice tongue which, at the peak of the last glaciation, extended down to El Manzanar, at 1200 m, 40 km downstream from the present glacier front which is located at 2500 m. Santana was unable to discover conclusive marks left by older glaciations, but he found evidence of a late-glacial advance restricted to the highest tributaries of the main valley.

Recent studies have not confirmed Brüggen's (1946) and Karzulovic's (1958) conclusions on the occurrence of old glacial deposits in the Santiago basin, which is a part of the Central Valley of Chile. The geomorphic map of the surroundings of the capital surveyed by Tricart (Tricart *et al.*, 1965) only shows torrential deposits of fluvioglacial origin at the foot of the high Cordillera. Cataclysmic volcanic mudflows are incorporated in them (Segerstrom *et al.*, 1964). According to Langhor (1971) unquestionable marks left by ice in the Central Valley are found from Chillan (36° 36′ S) southward. Habbe (1972) mapped deposits of three glaciations (Aussenmoräne, Höhenmörane, and Talmoräne) immediately west of where the Río Laja (37° 17′ S), a tributary of the Río Bío Bío, emerges from the Andean Cordillera.

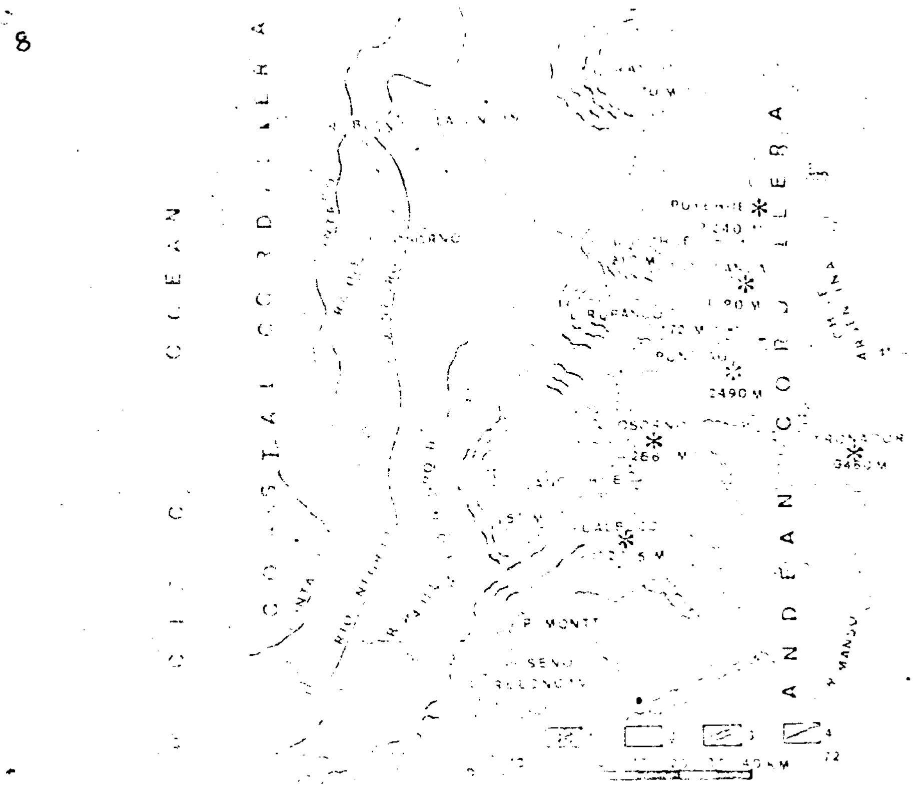
In the Coastal Range of central Chile, with summits rising above 2000 m, Pleistocene climatic changes started effective morphogenic processes on several occasions. More humid and cooler climates than the present one account for smooth slopes composed of layered screes above 1200 m (Borde, 1966) and inactive alluvial fans at their bases.

Data which improve our knowledge of the upper Pleistocene in central Chile can be drawn from new archaeological and paleontological findings (Casamiquela *et al.*, 1967), made near the Laguna de Tagua Tagua, in the Central Valley (34° 30′ S). The presence of *Antifer* sp. may indicate an interstadial warming 20,000–30,000 years ago (Casamiquela, 1969–1970). The large vertebrate fauna (*Mastodon, Mylodon, Equus*) disappeared after 11,000 BP (Montane, 1968; Casamiquela, 1969; Paskoff, 1971b) because of the Holocene climatic degradation but mainly because of the arrival of the first human hunters (Montané, 1972).

The Lake Region and Chiloé Island (39–44° S)

In the Central Valley of the Lake Region (39–41° S) Weischet (1964, 1970), who carried out detailed field investigations, found geomorphic remnants of four glaciations separated by distinct interglacial periods (Fig. 1). According to this author, during the oldest glaciation (Contaco glaciation) ice advanced as far as the eastern foot of the Coastal Range and reached the Pacific Ocean, north of the mouth of the Río Maullin. Terminal moraines were built, whose material is deeply weathered, including sizeable boulders mixed with a matrix of Tertiary paleosols. The second glacial advance (Rahue glaciation) stopped behind the line attained by the first one; it left moraines in which quartzitic boulders remained sound: kaolinite and halloysite are the main clay minerals (Besoain, 1964). In fact, the occurrence of two different glaciations is still debatable. Lauer (1968) only found evidence of one old glaciation to which very much obliterated till is ascribed. Besoain (1969) did not observe clear differences between the red clayey soils which cover the Contaco till and those developed on the Rahue till. In the surroundings of Valdivia, Illies (1960) merely mapped deposits of only one old glaciation. Recent studies conducted by Laugénie (1971; Laugénie *et al.*, 1975) and Mercer (1976a) also show remnants of an old glaciation (Fresia glaciation or Río Frío glaciation), but because Weischet's limit of glacial advance lies far to the west of any end moraine noted by these authors, no correlation can be attempted.

The next-to-last glaciation (Río Negro) is evidenced by two well-preserved end moraines. During the earlier stade, ice reached the axis of the Central Valley, but in the subsequent stade, it did not go as far. Tills of



[illegible] 1. Glacial [illegible] in the Chilean Lake region according to Weischet (1964 and 1970). [illegible] Quaternary strato-volcanoes [illegible] limit between the Andean Cordillera and the Central [illegible] last glaciation [illegible] (4) external limit of older glaciations (Rio [illegible]

[illegible] moraines are only partially altered. [illegible] pebbles remain unweathered. [illegible] by andesitic-basaltic ash, [illegible] the parent material [illegible] *trumaos* (Langhor, 1974). [illegible] are for andosoils characterized [illegible] mixed with allophane [illegible] *et al.*, 1973). The two stages of [illegible] Rio Negro [illegible] may be tentatively correlated with the Colegual and [illegible] glaciations described [illegible] (1975) in the western [illegible] of Lago [illegible] glacial features are fairly [illegible] preserved. In fact, this suggestion is [illegible] and further studies are needed.

The last glaciation (El S[illegible]) [illegible] Heusser [illegible] Chilean tongues which at that time [illegible] from the Andes, did [illegible] far beyond the piedmont where they formed lobes. Sizable end moraines were built up. Jointly with terminal overdeepening effects, they account for the string of Chilean sub-Andean lakes which range from Lago Riñihue southward to Lago Llanquihue, and even to the so-called Seno de Reloncavi, an arm of the sea, which would have been a lake similar to the others had it not been invaded by marine waters (Brüggen, 1950). The terminal lobate loops, several tens of meters high, generally consist of three ridges which appear well preserved, closely spaced but clearly defined. They are covered by volcanic ash, 1 to 2 m thick, on which well-drained *trumao* soils (andosoils) developed (Langhor, 1974). The sediment shows no sign of weathering, except a light alteration of

...ic matter is frequently embedded or ... with this youngest glacial drift, ... trunks of fallen trees and peat. ... dating (Mercer, 1972b, 1976a, ...; Mercer and Laugenie, 1973) and pol... analyses (Heusser, 1966a, 1972a, 1974, ...) have been carried out. The outer... ridge of the morainic belt, which ... surrounds the lakes and to which is linked a ... outwash plain, is estimated to be more than 56,000 years old. The middle ridge, sometimes split into two, may be about ...500 years old; the 36,000 BP ^{14}C date recently proposed for it by Mercer and Laugenie (1973) is now known to be unreliable (Stuiver, Mercer, and Moreno, 1975). Ice is believed to have withdrawn from the sites of the present lakes 15,300 years BP, at the time of the Varas interstade, but it advanced again and built up the innermost ridge, which is found along the western shore of the lakes, 2000 years later. According to Heusser's palynological studies, during glacial advances the climate of the Central Valley was definitely colder and drier than it is today: average July (the warmest month) temperature was 8°C instead of 16°C today; annual precipitation was less than 500 mm instead of 1 to 2 m today. The prevalent vegetation was then of tundra type: spores of *Lycopodium fuegianum*, which at the present grow in Tierra del Fuego, were encountered near the western end of the Lago Rupanco (41° S). On the contrary, at the warmest time of an early interstade of the last glaciation, the Andean tree line is estimated to have been about 900 m lower and the average January (summer) temperature about 3–4°C colder than at present. Mercer thinks that, after the last readvance, which culminated about 13,000 BP and ended the last major glaciation in southern Chile, a rapid deglaciation followed. By analogy with what he observed in southernmost Chile near lat 49° S (Mercer, ...) he also assumes that glaciers were confined within the Cordillera at about 12,500 BP and were smaller than they are now by 11,000 ... 11,000 and 10,000 BP, but geomorphic evidence indicating such a glacial readvance has not been found.

The postglacial history of southern Chile is not yet well established. Morainic accumulations observed here and there in the upper courses of Andean valleys may be deposits of retreating glaciers rather than deposits of Holocene readvances. Following Heusser's palynological results, climate warmed up to a maximum 1–2°C higher than the present during the Hypsithermal which took place between 8500 and 6500 BP; under rising temperature the Valdivian rain forest developed and became extensive. Afterward, a first Neoglacial cooling characterized by temperatures of about 2°C below today's occurred between 5500 and 4500 BP, and the Valdivian rain forest lost ground in favor of the north Patagonian rain forest.

In the Coastal Range, which during Quaternary glaciations remained beyond the reach of ice advances, recurring periglacial conditions are documented by slope colluvium. In the surroundings of Valdivia, sections show four generations of layered screes which Weischet (1966) correlated with the four above-mentioned glaciations he found in the Central Valley.

The glacial record of Chiloé Island is incompletely known. Brüggen (1950) described morainic deposits in the eastern part of the island. But, according to Stiefel (1968), material outcropping on the cliff of the northeastern coast is of glacial–marine origin. Elsewhere, Saliot (1969) found only glacio-fluvial or glacial-lacustrine deposits. However, investigations recently completed by Heusser and Flint (1976), recognize three offlapping layers of Quaternary glacial drift, deposited on a lowland by piedmont glaciers of Andean origin; they are, respectively, thoroughly decayed (oldest drift), partly decayed (intermediate), and fresh (young). The ... an extraordinary amount ... the western limit of glaciation trending southwest ... the P... near 42°...

Owing to its difficult access, the Fjord Region is still less known than Chiloé Island. After a field reconnaissance, Levi *et al.* (1966) proposed the name of Llahuén formation for a sequence of clastic volcanic sediments which at least in part may have originated as glacial deposits and which crop out along the Fjord coast between 41° 30' and 44° S. At the eastern foot of the Andes, thick and extensive lacustrine deposits in the Coihaique area (45° 30' S) are thought to have been laid down in a huge body of water dammed by glacier ice during the late-glacial recession (Stiefel, 1968). The western limit of glaciation between 44 and 46° has been recently drawn by Fischer (1974); according to him it extended beyond the edge of the continental shelf. Farther south, still on the western side of the Andes, the problem of late Pleistocene environmental changes was investigated in the Laguna San Rafael area (46° 40' S) by Heusser (1960, 1964), Muller (1959a, 1959b, 1960), and Lawrence and Lawrence (1959). Heusser assumes that the moraine ridges (Tempanos moraines), forming the laguna rim, were built up by a Neoglacial expanded foot phase of San Rafael glacier by 5000–4000 BP. Muller, however, considers that the Tempanos advance occurred prior to 9000 BP. A fairly good record of observations since the end of the 17th century points to repeated recessions and advances over several kilometers of San Rafael Glacier, which pushes out into the eastern waters of the laguna. Near Puerto Eden (49° 10' S) on Wellington Island, palynological studies (Heusser, 1972b) show a return of montane nonarboreal species, principally *Empetrum*, at the expense of the *Nothofagus* forest by 5000 BP; this return is interpreted to result from an important glacier readvance.

In the southernmost part of Chile, the glacial geology of the approaches of Magallanes Strait and Tierra del Fuego has been thoroughly investigated for more than four decades by Auer, who published

three main glacial advances took place during Quaternary time. The eldest glaciation, the most powerful since the ice reached the present seashore south of latitude 51° 30' S, is responsible for the widespread deposition on the Patagonian piedmont of the well-known *rodados patagonicos* or *Tehuelche gravels* that subsequently have been reworked by running waters. After a long interglacial age, two other glaciations occurred, separated by a warmer and wetter period during which volcanic activity increased. Recently Riggi and Fidalgo (1969) rejected a primary glacial source for the *Tehuelche gravels* and suggested that they originated through pediment processes which mainly took place in Pliocene time. Mercer (1969a, 1972a, 1973a,b, 1976a; Mercer *et al.*, 1975; Fleck *et al.*, 1972), however, considers that they represent mid-Pliocene to early Pleistocene glacial outwash gravels deposited during an interval of about 2.5 million years. They are interbedded with basaltic lava flows which have been radiometrically dated (K/Ar method) south of latitude 49° S. According to this author, the earliest glacial event was a major mid-Pliocene expansion of the ice about 3.5 million years ago toward the end of the Gilbert Reversed Epoch; it perhaps corresponds to the initial formation of the ice sheet in west Antarctica. Inconclusive evidence suggests that the entire Gauss Normal Epoch was nonglacial, with ice confined to the Cordillera. During the Matuyama Reversed Epoch, glaciers repeatedly expanded over the Patagonian piedmont as much as 2.08 million years ago, with the greatest glaciation occurring after 1.25 and perhaps before 1.03 million years ago.

The three main units of glacial drift (Pichileufú, El Condor, and Nahuel Huapi, in order of decreasing age), which have been identified by Flint and Fidalgo (1964, 1969) along the eastern shores of the Argentine lakes between 39° 10' and 43° 10' S lat, are also recognizable in the surroundings of the

These authors suggest that the weathering displayed by the above-mentioned drifts may reasonably indicate a Wisconsin age although the oldest drift could conceivably be pre-Wisconsin. The youngest drift corresponds to a late-glacial readvance which is radiometrically undated but probably older than 12,500 BP (Mercer, 1968). Afterward the ice receded on the eastern as well as on the western side of the Cordillera, and by 11,000 BP glaciers were smaller than they are today, implying the start of the hypsithermal interval, during which important changes affected the hydrographic network (Dresch, 1971). Three Neoglacial advances culminated at the beginning of the Subboreal about 4600–4200 BP, during the Subatlantic between 2700 and 2200 BP, and during the last centuries. Between readvances glaciers receded to within their present borders (Mercer, 1970a).

General Considerations

Whether Pleistocene climatic changes in the northern part (pluvial episodes) and southern part (glacial episodes) of Chile were synchronous or not is a major problem which remains to be solved, because the meteorological model accounting for them is still debatable. For instance, Nogami (1972) assumes that the atmospheric circulation pattern during the last glaciation was similar to the present one, and that the Wisconsin snowline depression in the Andean Cordillera was mainly caused by a cooling of the atmosphere. However, Paskoff (1970), Hastenrath (1971), Caviedes (1972b), and Suzuki (1973) infer that the southern polar front was displaced 5 to 6° northward during the Wisconsin glacial age. If Van der Hammen's opinion (1974) on the contemporaneity of climatic changes in tropical Andes with those recorded in higher latitudes is correct—and it seems so on the basis of ^{14}C dating—the intertropical convergence (ITC) was also displaced south-
ward at the same time. This implies ...

pressure cell (Dollfus, 1973) and consequently a narrowing of the arid belt (Dresch, 1973). But such a view is not shared, for instance, by Fairbridge (Damuth and Fairbridge, 1970; Fairbridge, 1972), who suggests that the ITC was shifted northward during the Quaternary glacial advances in the temperate zone of South America, causing a reduction in rainfall in the tropical latitudes.

Quaternary climatic changes were of glacial or periglacial type in southern and southernmost Chile on the one hand and in the Andean highlands of northern Chile on the other hand. They were of pluvial type in central and northern Chile, except in the high Andes. These climatic changes were characterized by a decrease of average temperature, at least in the southern half of the territory, and by a decrease of precipitation in the southern and southernmost part of the country, but by an increase of precipitation in central and northern Chile (Paskoff, 1971a). If the two last glaciations which affected the high Andes are relatively well known, the number as well as the spatial extension of older glaciations are still unclear, and further investigation is needed, particularly in the Lake Region.

Finally, these climatic changes show a general parallelism with those evidenced in a similar geographic situation in the Northern Hemisphere, at least within the limits of radiocarbon chronological control (Heusser, 1961, 1966b, 1973; Paskoff, 1976a). However, the Younger Dryas cooling at about 11,000 BP, clearly established in northwest Europe, is still under discussion in South America as well as in New Zealand (Mercer, 1969b, 1974). Neoglacial fluctuations in both hemispheres show an in-phase relationship for the most part, but the advance which culminated at the beginning of the Subboreal was much more pronounced in Patagonia and in New Zealand than in the Northern Hemisphere where it was a rather minor event (Mercer, 1967, 1970b). On the contrary, the Subatlantic readvance seems to have been more important in the Northern Hemisphere than in the southern one.

SEA LEVEL FLUCTUATIONS

Detailed paleontological and geomorphic research recently carried out along the central and northern coast of Chile (Herm, 1969; Paskoff, 1970; Caviedes, 1972a) has led to a coherent scheme of sea level fluctuations during Quaternary time. At least in the above-mentioned part of the Chilean coast, it appears that glacio-eustatic variations played a significant role from a geomorphic point of view even if tectonic disturbances, strong in some places, weak in others, also took place (Segerstrom, 1963; Segerstrom and Cooke in Fuenzalida *et al.*, 1965; Borde, 1966; Alvarez, 1966; Mortimer, 1969, 1973). In this respect Coquimbo Bay (30° S) and surroundings represent a unique and impressive site (Paskoff, 1972) because of its relative stability, the clearness of abandoned cliffs and extensive wave-cut platforms occurring between 120–130 m and present sea level, and the wealth of fossiliferous beach deposits (Figs. 2 and 3). A 1:50.000 scale colored geomorphic map of the Coquimbo Bay area is available (Paskoff, 1970), and detailed stratigraphic, paleontologic, and paleoecologic data have been published by Herm (1969).

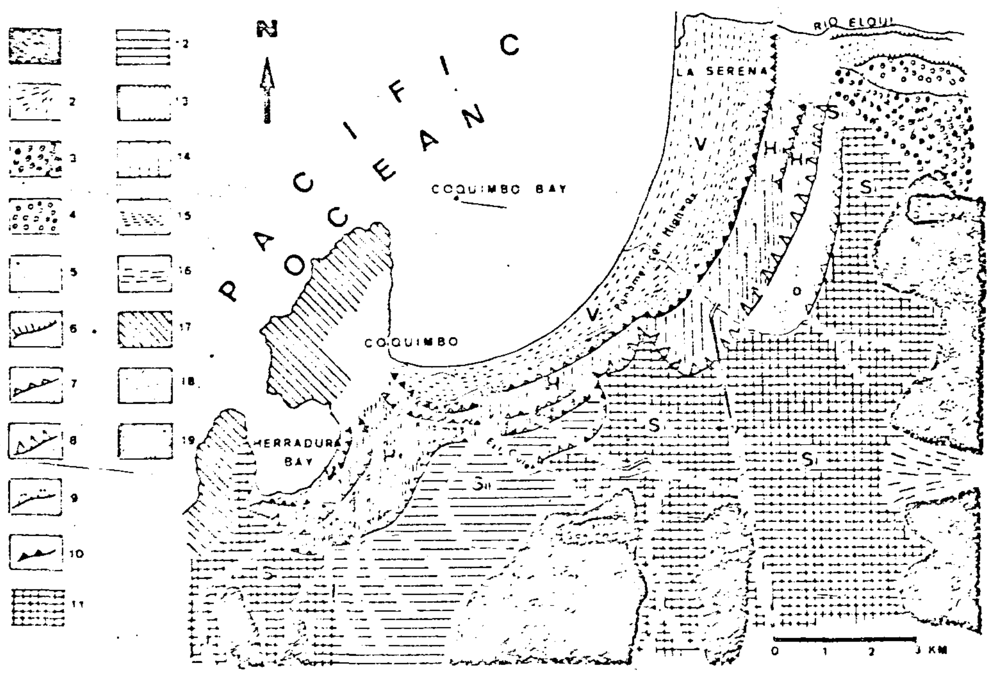


FIG. 2. Quaternary marine terraces around the southern part of Coquimbo Bay, according to Herm and Paskoff (1967): (1) bedrock not reached by Quaternary transgressions; (2) alluvial fan; (3) lower Pleistocene fluvial terrace; (4) middle Pleistocene fluvial terrace; (5) Holocene fluvial terrace; (6) edge of fluvial terraces; (7) abandoned cliff (less than 20 m high); (8) abandoned cliff (more than 20 m high); (9) assumed abandoned cliff; (10) abandoned cliff of Cachagua stage; (11) marine terrace of the Serena I stage (lower Pleistocene); (12) marine terrace of the Serena II stage (lower Pleistocene); (13) marine terrace of the Herradura I stage (middle Pleistocene); (14) marine terrace of the Herradura II stage (middle Pleistocene); (15) loose marine sediments of the lower Vega stage (lower Holocene); (16) loose marine sediments of the middle Vega stage (middle Holocene); (17) bedrock eroded by marine abrasion during Quaternary time; (18) eolian deposits (D = dunes); (19) buildings.

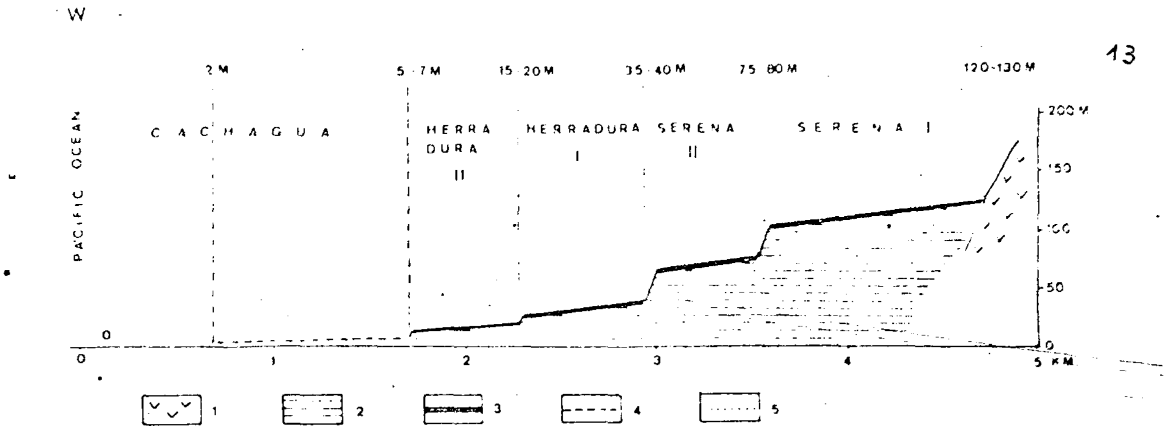


FIG. 3. Cross section showing Quaternary marine terraces just south of La Serena (Coquimbo Bay area), according to Herm and Paskoff (1967): (1) bedrock; (2) upper Pliocene (Coquimbo formation); (3) marine deposits of the Pleistocene marine stages; (4) marine deposits of the lower Holocene; (5) marine deposits of the middle Holocene.

The Pliocene–Pleistocene Boundary

The Tertiary Era ended with a transgression which began in the middle Pliocene and left the Coquimbo Formation (Hoffstetter *et al.*, 1957). This formation is made up of yellowish to greyish, poorly cemented sandstones characterized by fine to medium sand, a sublittoral to neritic facies, and abundant fossils. Molluscan assemblages point to a faunal province showing considerable influence from the neighboring Pacific realm toward the north, in contrast to the Miocene faunas marked by a majority of Atlantic genera. From middle to late Pliocene endemic evolution of several groups (i.e., the Pectinids and the Venerids) can be demonstrated. On the whole, Pliocene faunas show a much closer affinity to the present Panamic province, characterized by numerous warm-water genera and species, than the fauna does at present (Herm, 1969). The Quaternary begins with a conspicuous regression—the Tongoyan regression (Paskoff, 1968)—whose deposits, including continental mollusks (Herm, 1970), are separated by an erosional unconformity from those of the Coquimbo Formation. Where the Tongoyan deposits are locally preserved, they are in turn capped by marine sands and pebbles laid down by the first Pleistocene transgression.

Quaternary Marine Conditions along the Central and Northern Coast of Chile

From a geomorphic point of view, Quaternary transgressions generally left striking sets of step-like marine terraces—five around Coquimbo Bay—each separated from the other by steep abandoned cliffs. These landforms, generally well preserved, were cut either into soft Pleistocene sandstones of the Coquimbo Formation or more resistant pre-Tertiary rocks.

Quaternary deposits are rather thin generally consolidated beach sediments, in which sands, pebbles, and shells are mixed. It is sometimes possible to distinguish transgressive deposits from regressive deposits; the former often include rock fragments taken from the substratum, resembling basal conglomerates, whereas the latter are mainly stratified sands with few pebbles (Paskoff, 1970).

The beginning of the Pleistocene corresponds to a second, more pronounced move toward isolation and endemic development of the marine fauna. This change includes the fauna from all biotopes and is apparent through (1) an increasing reduction of genera (*Anomia*, *Panope*, etc.), mostly forms desiring warmth; (2) reduction of the number of species, especially among the genera *Chlamys* and *Chorus* (for instance, only one *Chlamys* is found in Pleistocene deposits, *Chlamys purpurata*, in contrast to five in Pliocene deposits); (3) substitution of the dominant species in the faunal communities; and (4) extensive development of several species which appeared in the Pliocene as accessory forms (*Mesodesma donacium*, *Mulinia* div. sp.).

At the beginning of the Pleistocene a weak new immigration of species occurred from the northerly Panamic faunal province; these species, however, were expelled again during the middle Pleistocene, pointing to a cooling of the Humboldt Current. In fact, the fauna remains relatively constant through the Pleistocene and appears to be quite similar to that of the Holocene (Herm, 1969).

Quaternary Marine Stages

At least six marine stages, each characterized by a transgression, a standstill, and a regression, are evident. Data dealing with each of these stages are summarized in Table 2, slightly modified from Herm and Paskoff (1967).

South of 33° S lat available field observations still remain too discontinuous for testing the above-mentioned marine Quaternary model set up for the central and northern coast of Chile. However, scattered data point to the important role played in the geomorphology of the continental margin by glacio-eustatic fluctuations which interfered with tectonic movements. According to Stiefel (1974), the southern coast of Chile was differentially raised, without faulting of any significance, and glacio-eustatic oscillations were superimposed on the upward movement. Fuenzalida *et al.* (1964) attribute to sea level changes the marine terraces of the San Antonio and Carthagena area (33° 35′ S). Tricart (1971–1972) mentions marine platforms between 35 and 36° S lat, which he believes are of glacio-eustatic origin and tectonically uplifted. Around the Río Bío Bío mouth, near Concepcion (36° 50′ S) deposits slightly above present sea level are ascribed by Martinez (1968) to the worldwide Holocene transgression, but according to Galli (1968), they have been affected by recent crustal deformations. In the same way, Stiëfel (1968, 1974) assumes that glacio-eustatic changes interfering with tilting and faulting account for the geomorphic features of the Arauco peninsula (37° 31′ S) which consist of five main marine terraces. According to Kaizuka (Kaizuka *et al.*, 1973), each surface was made under a Quaternary marine transgression, probably caused by a eustatic rise of sea level; the Cañete surface, the widest among them, is ascribed to the last interglacial. In the surroundings of Valdivia (39° 48′ S) Weischet (Fuenzalida *et al.*, 1965) reported evidence of discontinuous marine terraces at 1–2 (today practically submerged because of subsidence that occurred after the powerful earthquakes of May, 1960), 10–15, 20–25, 30–35, 70, and 170–200 m: if Lauer's (1968) hypothesis is correct, the first two levels would be, respectively, of Holocene and Sangamon age. Marine terraces found at distinct levels have been identified along the northwest coast of Chiloe Island, near Chepu (42° 04′ S), but no correlation has been attempted (Watters and Fleming, 1972).

Quaternary marine conditions in the Fjord Region are practically unknown. Scattered data available for southernmost Chile will be presented in the third part of this report in connection with crustal movements linked with glacial–isostatic rebound.

Relationship between Marine and Terrestrial Deposits

About this important problem, it is necessary to clearly distinguish between short, intermittent streams presenting steep profiles, such as the so-called *quebradas* which run down from the Coastal Range in

TABLE 2

THE QUATERNARY MARINE STAGES IN CENTRAL - NORTHERN CHILE"

	Marine stages	Ocean oscillations	Height above sea level Coquimbo Bay area (meters)	Landforms and deposits	Fauna	Archaeology	Absolute ages
Holocene	Vega Middle	Regression Slight regression or standstill	0 2	Present shoreline Dunes Sand bars		Diaguitas El Molle	2000 BP
	Lower	Regression Max. transgression Transgression Max. regression	4–5	Loose sediments on the lower terrace	No appreciable changes	"Anzuelo de concha"	4000 BP
Upper Pleistocene	Cachagua	Regression Max. transgression Transgression Max. regression	5–7	Lower terrace and dead cliff at 5–7 m			35,000 BP
Middle Pleistocene	Herradura II	Regression Max. transgression Transgression Max. regression	15–20	Second middle terrace	Swarm of *Transennella pannosa*		
	I	Regression Max. transgression Transgression Max. regression	35–40	First middle terrace	Vanishing of *Ostrea ferrarisi*		
Lower Pleistocene	Serena II	Regression Max. transgression Transgression Max. regression	75–80	Dune High terrace	Appearance of *Mesodesma donacium*, *Malinia* sp., *Chlamys purpurata*, *Laevicardium grande*, *Protothaca thaca*, *Turritella cingulata*		
	I	Regression Max transgression Transgression Max. regression	120–130	Highest terrace Continental deposits (Tongoyan)			
Upper Pliocene	Coquimbo Formation	Regression Max. transgression	200		*Chlamys vidali* *Chlamys calderensis* *Chlamys hupeanus*		

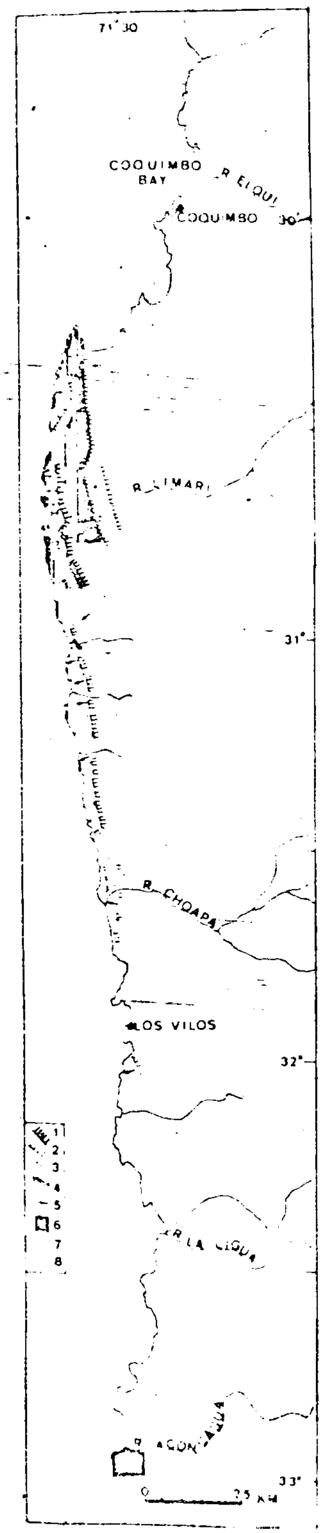
northern Chile and permanent rivers with smooth profiles, which flow down from the high Andes farther south. In the first case, thick alluvial deposits have been laid down by streams on emerged beaches during pluvial periods corresponding to glacio-eustatic regressions, as stressed by Dollfus and Tricart (1967). On the contrary, in the second case, alluvial deposition took place in the lower courses of rivers, because of rising sea level at the beginning of inter-pluvial or interglacial periods, and not because of direct climatic control which is, in fact, responsible for aggradation only in the upper courses of rivers under rainy and or cold conditions. Observations made between 28° 30′ and 39° 50′ S by Cooke (1964) along the Río Huasco, by Paskoff (1970) along the Río Elqui, by Caviedes (1972a) along the Río Aconcagua, and by Lauer (1968) along the Río Valdivia are in good accordance with this point of view.

TECTONIC DEFORMATION

Syntheses dealing with Chilean geology published about 10 years ago (Zeil, 1964; Ruiz, 1965; Corvalán, 1965) are still strongly influenced by Brüggen's (1950) and Muñoz Cristi's (1956) ideas on Quaternary uplift of the Andes. According to such a short chronology, the main orographic units of Chile (Andean Cordillera, Central Valley, and Coastal Range) would have been individualized only from the beginning of Pleistocene time when a Tertiary matureland was strongly faulted. Consequently, only the diastrophic control was taken into account to explain fluvial and marine terraces: authors such as Polanski (1965) following Heim (1951), assumed that the Andes were not uplifted to sufficient altitude to support glaciers before the last glaciation, an assumption that appears to be definitely wrong. As a matter of fact, recent tectonic deformations were thought to be major factor of geomorphic evolution in Quaternary time. However, recent geomorphic studies (Borde, 1966; Mortimer 1969, 1973; Mortimer and Saric, 1975; Hollingworth, 1964; Paskoff, 1970; Stiefel, 1971, 1972), carried out in northern and central Chile led to new views supported by an increasing number of K/Ar age determinations of volcanic rocks (Rutland *et al.*, 1965; Clark *et al.*, 1967; Mortimer *et al.*, 1975). As a result, it appears that the major uplift of the Andes took place at the end of the Miocene or, at the latest, at the beginning of Pliocene time ("geographical phase" of Vicente, 1972). For example, the wellknown high cliff of northernmost Chile, traditionally interpreted as a Quaternary fault scarp, is now considered to be the result of faulting at the end of the Miocene time followed by marine erosion during Pliocene time (Mortimer and Saric 1972; Paskoff, 1973b, 1976b). In the same way, much of the faulting in the southern Atacama Desert probably occurred well before the beginning of Quaternary time (Cooke and Mortimer, 1971). Adopting such a long chronology implies a reassessment of the effects of Pleistocene crustal movements which, in fact, remain important and sometimes striking phenomena, as can be expected in a segment of the circum-Pacific active continental margin.

Characteristics of Quaternary Tectonic Deformation

In a way, Quaternary crustal movements represent the prolongation of extensional motion characteristic of the so-called post-liminar period of the Andean Cordillera (Aubouin and Borello, 1966, 1970; Aubouin *et al.*, 1973). Thus, the Quaternary tectonic status seems to be extension and not compression expected as sea-floor spreading compensation (Katz, 1971; Charrier, 1973). Normal faults limiting uplifted, downwarped and tilted blocks are common (Aubouin, 1971). Folds are rarely found. Suspected strike-slip faults (Saint-Amand and Allen, 1960; Allen, 1962, 1965) so far have not been proved unquestionably (Katz, 1970).



Some examples of Quaternary crustal movements have striking topographic expression. Southeast of Iquique, according to Okada (1971), a suggestive fault scarp disrupts talus cones developing along the eastern foot of the mountain which limit the Salar Grande (21° S) on its western side. Brüggen (1950) was the first to describe a scarp near Antofagasta, a few meters high and several kilometers long, that cuts an alluvial fan built up during the last pluvial period of the Pleistocene at the eastern foot of the Coastal Range, on the northwest edge of the Salar del Carmen (23° 55′ S). As a matter of fact, both scarps correspond to segments of a major north-trending fault zone, called the Atacama fault (Arabasz, 1968), which runs parallel to the coast as far as the Copiapó region. In the lower course of the Río Copiapó, a north-northeast striking fault which crosses the valley near Monte Amargo (27° 20′ S) is reported by Segerstrom (1965). It has disrupted an early Quaternary high streram terrace, dropping the eastern block 40 to 50 m with respect to the western block; however, a lower terrace of Holocene age (Mortimer *et al.*, 1971) appears not to be affected by the fault scarp.

On both sides of the Río Limarí mouth, Paskoff (1970) mapped wave-cut platforms dating back to the late Pliocene and early Pleistocene, strongly uplifted along faults, several hundred meters high and forming the Talinay Heights which culminate at 667 m just above the Pacific Ocean (Fig. 4). In the Santiago basin, a graben between the Andes Cordillera and the Coast Range, fluvioglacial sediments from successive Pleistocene glaciations in the Cordillera have been piled up one upon another as a result of subsidence

FIG. 4. Quaternary crustal movements along the Chilean coast between latitude 30 and 33° S, according to Paskoff (1970): (1) fault scarp (throw more than 100 m); (2) fault scarp (throw between 10 and 100 m); (3) fault scarp (throw less than 10 m); (4) assumed strike slip fault; (5) tilting; (6) strongly uplifted area; (7) uplifted area; (8) downwarped area.

(Tricart *et al.*, 1965). Nevertheless, the sediments filling the Santiago basin, in places several hundred meters thick, are not entirely of Quaternary age. In fact, most seem to have been laid down in Pliocene time as a consequence of the uplift of the Andes and during an important episode of effective torrential dissection (Paskoff, 1970).

A general analysis of Quaternary crustal movements throughout Chile leads to a division of the territory into three main provinces, each one characterized by an original neotectonic trend (Gajardo and Lomnitz, 1960; Lomnitz, 1962): (1) the northern province, between latitudes 18 and 26° S, shows indications of continuing uplift; even the Central Valley, here called Pampa del Tamarugal, in fact is not a true graben but a block less uplifted than the adjacent ones (the Andean highlands on its eastern side, the Coastal Range on its western side) (Tricart, 1966; Cecioni, 1970); (2) the north-central province, between latitudes 26 and 33° S, shows a relative stability which appears to be in close relationship with the absence of the Central Valley and Quaternary volcanism in this part of Chile; (3) the southern province, between latitudes 33 and 46° S, shows an important subsidence, evidence of which is given by the increasing thickness of Pliocene–Quaternary sediments in the Central Valley south of Santiago (500 m at Santiago, 33° 27′ S; 1000 m at Chillán, 36° 36′ S; 4000 m at Puerto Montt, 41° 28′ S) and the drowning of the valley by the Pacific Ocean south of Puerto Montt (Kausel and Lomnitz, 1969).

Recent geological studies (Stiefel, 1971, 1972) indicate that each of these provinces is made up of independent segments which have been affected unequally by widely uniform epeirogenic movements. For instance, the Chilean coast of the intermediate province (26–33° S) shows three segments (Fig. 4): a segment between 30° 10′ and 31° 45′ S has been strongly disturbed by neotectonic deformation; meanwhile, adjacent segments remained relatively quiet. Such a differentiation may reflect discontinuities on the underlying subduction zone, if Sillitoe's (1974) hypothesis is correct.

In southernmost Chile, beyond latitude 46° S, where the Patagonian Andes are still largely covered by ice, glacio-isostatic rebound is likely to have played an important role as a geomorphic factor in Holocene time. Raised marine terraces have been reported along the coasts of Madre de Dios and Jorge Montt Archipelago, Magallanes Strait, and western Tierra del Fuego Island (Auer, 1959, 1970; Cecioni, 1957). Similarly, in the South Shetland Islands, near the Antarctic Peninsula, beaches and wave-cut beaches perched above present sea level have been described (Araya and Hervé, 1966). All above-mentioned authors logically postulate an interaction between glacio-eustatic fluctuations and glacio-isostatic crustal movements to account for such emerged coastal features. Cecioni (1957), followed by Katz (1962), also assumes that, independent from glacio-isostatic rebound, Patagonia has been tilted during Quaternary time with upwarping on the Pacific side. Unfortunately, quantitative data dealing with Holocene glacio-isostatic uplift of the Chilean Fjord coast are lacking because of the scarcity of ^{14}C dates on fossiliferous beach deposits (Richards, 1966, 1968).

Present Active Faulting

Oddly enough, topographic surveys and geologic studies carried out just after the major earthquakes which have occurred in Chile for the last 15 years have not given evidence of unquestionable fault displacements (Lomnitz, 1970; Arabasz, 1970), whereas striking examples of present active faulting are well known in such other tectonic regions as Peru, California, and Japan (Allen *et al.*, 1971). Numerous observations, however, show that the great earthquake sequence of May 21–22, 1960, which affected southern Chile between latitudes 37 and 48° S, was accompanied by tectonic warping, including both uplift and

Involved region, which is more than 200 km wide and about 1000 km long, vertical tectonic displacements resulted in an uplift of the continental shelf of at least 5–7 m, a subsidence of as much as 2–3 m of the Coastal Range and the Central Valley, and a slight uplift of less than 1 m of the western margin of the Andes (Plafker and Savage, 1970). The pattern of surface deformation suggests a displacement along a major thrust fault approximately 1000 km long and having an average dip of 35°. The fault intersects the sea floor in the vicinity of the Peru–Chile trench. The 1960 earthquake implies a dip–slip movement on the fault plane of close to 20 m which can be explained by the release of elastic strain energy accumulated by the underthrusting of the East Pacific plate migrating eastward at more than 5 cm/year under the Americas plate migrating westward at 2 cm/year (Plafker, 1972).

QUATERNARY VOLCANIC ACTIVITY

In conterminous Chile, Quaternary volcanic rocks crop out over more than 50,000 km² (Levi, 1965). With the exception of olivine basalt lava flows of probable Holocene age (Altevogt, 1969) found on the Patagonian plateau 130 km northeast of Punta Arenas (53° 10′ S) near the Argentinian border, all these volcanic rocks originated in the high Cordillera. The Coastal Range remained entirely beyond the reach of Pleistocene volcanic activity. In the high Cordillera, two provinces may be clearly distinguished—the northern province (17° 30′–27° 30′ S) and the central and southern province (35° 15′–52° 20′ S) (Corvalán *et al.*, 1968; Vergara, 1970; Vergara and Gonzáles, 1972; Katsui, 1972; Pichler and Zeil, 1971, 1972).

Northern Chile (17° 30′–27° 30′ S)

Knowledge of Cenozoic volcanism in northern Chile has made great strides in the last decade (Zeil, 1963, 1964; Dingman, 1965; Zeil and Pichler, 1967; Katsui and Gonzales, 1968; Hollingworth and Rutland, 1968; Pichler and Zeil, 1969a, b; Francis *et al.*, 1975). Volcanic activity which began in Neogene time went on during the Quaternary with new characteristics.

Huge outpourings of fissure lava and pyroclastics built an extensive plateau of rhyolitic ignimbrites during the late Miocene and throughout the Pliocene, in close relation with the extensional tectonic phase which gave rise to the uplift of the Andes (Hollingworth, 1964; Guest, 1969). Such volcanic products, interbedded with detrital continental deposits, reach thicknesses ranging from 400 to 1000 m and have been given a variety of local formational names: Rhyolite Formation (Brüggen, 1950); Altos de Pica Formation (Galli and Dingman, 1962); Oxaya Formation (Salas *et al.*, 1966). They cover more than 75,000 km² in Chile, but they also are found in Peru, Bolivia, and Argentina, covering in total more than 150,000 km² (Fig. 5). Ignimbrites range from alkalic rhyolite to rhyolite and rhyodacite. Zeil and Pichler (1967) pointed out the anatectic origin of these rocks: the rhyolitic magma was formed by the melting of sialic material in the upper part of the crust. K/Ar determinations (Dingman, 1965; Rutland *et al.*, 1965; Clark *et al.*, 1967) indicate that they are late Miocene to Pliocene in age (12.6 to 4.2 million years). Recently however, Mortimer *et al.* (1975) estimated on the basis of new radiometric dates that their deposition might have commenced in the early Miocene or even before. In Chile, Tertiary ignimbrites that spread from the high Cordillera to the low-lying Pampa del Tamarugal form extensive plateaus which are dissected and inclined westward, except where tectonic movements have modified the original slope.

During Quaternary time, volcanic outpourings displayed new characteristics. They are confined within the highest areas of the Andean Cordillera, near the Bolivian and Argentinian borders, and volcanism is of the central type. Approximately 500 stratovolcanoes have been built upon the *altiplano*, which is a plateau situated at an

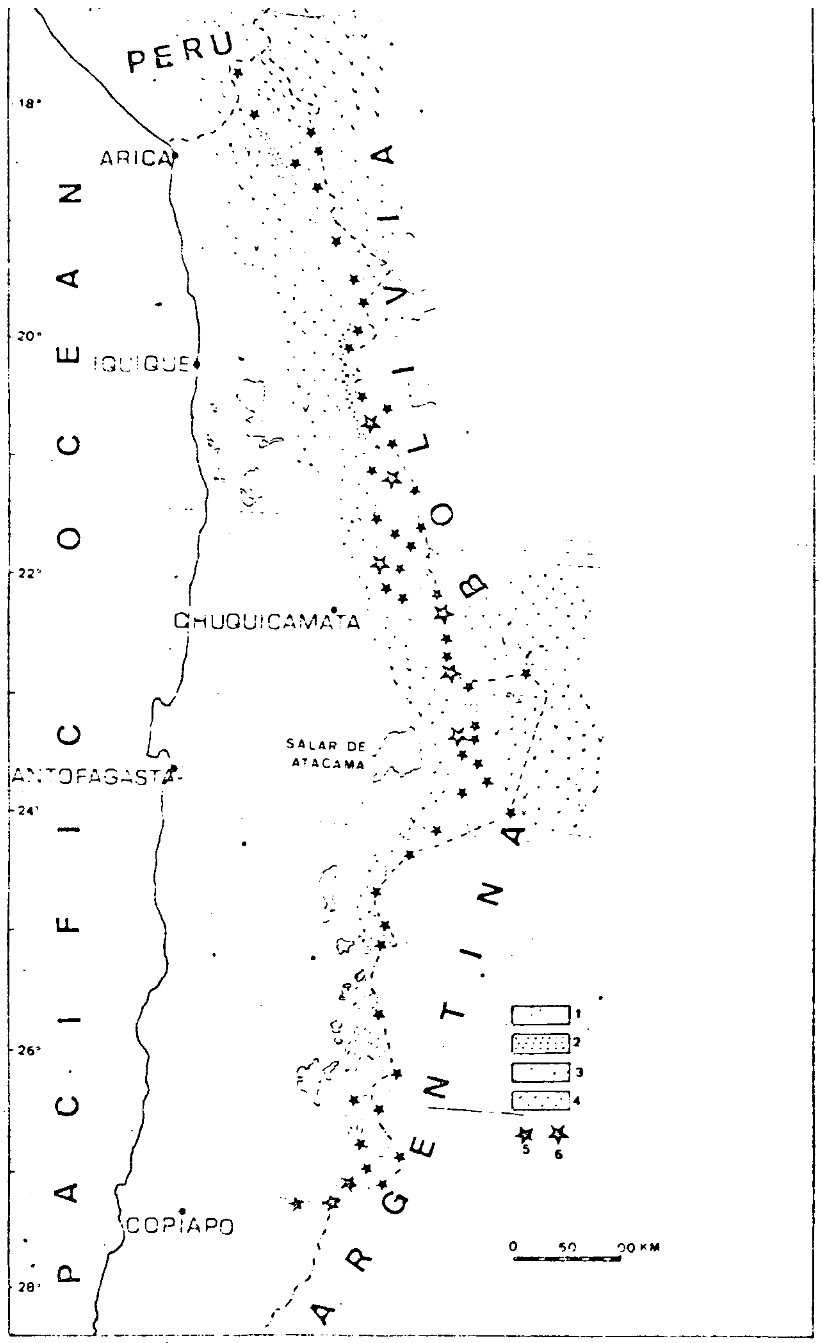


FIG. 5. Cenozoic volcanic areas in northern Chile, according to Zeil (1963). (1) salars; (2) pumice fields; (3) Quaternary Andesite formation; (4) upper Tertiary Rhyolite formation (predominantly ignimbrites); (5) dormant strato volcano; (6) active strato volcano.

average altitude of 4000 m, and many reach 6000 m or more. They form an imposing chain, approximately parallel to the strike of the Cordillera, over more than 10° of latitude. The volcanoes follow tectonic trends, mainly in echelon faults that genlineaments (Miller, 1967). Calderas, lava domes, and lava flows are found in addition to stratovolcanoes. The bulk of the Quaternary volcanic rocks belongs to the so-called Andesite Formation. Quartz-bearing latite-andesites are predominant, but lavas of acid composition, dacites (Guest and Sanchez, 1969), and rhyodacitic ignimbrites (Roobol *et al.*, 1974) have also been described. No Basalts were found. According to Pichler and Zeil (1969a, b, 1970, 1971, 1972), there is evidence that the andesitic magma originated by partial fusion of material of the lower, degranitized parts of the crust. Pleistocene stratovolcanoes were affected by glacial erosion. During the Quaternary, a migration of volcanic centers from the northeast to the southwest occurred. Present activity is sporadic and weak; it is mainly restricted to fumaroles, solfataras, and geysers.

Pseudovolcanic features have been reported in the Chilean desert. Thomas (1969) described a distinctive group of craters of probable meteoritic origin, near the Quillagua oasis (21° 30′ S). A crater whose meteoritic character is verified by particles of impact origin has been discovered at 23° 55′ S and 68° 16′ W by Sánchez (Sánchez and Cassidy, 1966).

Central and Southern Chile (33° 15′ – 52° 20′ S)

There is a conspicuous volcanic gap in Chile between latitudes 27° 30′ and 33° 15 S, where Andean summits reaching altitudes of 5000 to 6000 m are not volcanoes. This marked lack of volcanism closely corresponds to the vanishing of the Central Valley and a clear decrease in seismic activity (Stauder, 1973). Perez and Aguirre (1969) supposed that low-angle reverse faults, which characterize this zone of Chile, may have sealed magmatic channels, hindering the outpouring of volcanic material. New hypotheses dealing with plate tectonics recently have been suggested by Mortimer (1973) and Drake (1974): a slower ducting lithosphere may have resulted in reduced magma generation.

Quaternary volcanism reappears at the latitude of Santiago. At first it remains limited to the crest of the high Cordillera; then, from latitude 38° S, it comes closer to the Central Valley (Fig. 6). As a matter of fact, a significant westward migration of major centers of volcanism appears to have taken place in the late Pleistocene from the present drainage divide, probably related to a change in the Benioff seismic zone (Drake, 1974; Vergara and Munizaga, 1974). South of latitude 42° S, Quaternary volcanism becomes rarer and Mount Burney (52° 20′ S) is apparently the southernmost Chilean volcano. The vanishing of volcanism in the Fjord Region closely corresponds to the intersection of the Chile Ridge with the continental margin (Chotin, 1975). Present volcanic activity is stronger and more extensive in central and southern Chile than in northern Chile (Casertano, 1963). Numerous volcanoes show violent sporadic explosive eruptions (Gonzáles, 1972a).

Detailed geological studies backed by numerous radiometric dates (Vergara and Munizaga, 1974) permit characterization of the Quaternary volcanism within the Cenozoic magmatic cycle. For instance, the Cola de Zorro Formation, cropping out between latitude 35 and 38° S and formerly considered Pliocene–Quaternary in age (Gonzáles and Vergara, 1962), is now more reasonably assigned to the Miocene (Thiele and Katsui, 1969). It is composed of andesitic lavas of the calc-alkaline series, 400 to 800 m thick, discordantly resting on folded and beveled Mesozoic rocks; it forms a plateau that has been strongly affected by faulting during the uplift of the Andes, and deeply dissected. Andesitic lava flows covering erosional benches noticeable on slopes of the main valleys are probably Pliocene in age; they were erupted during the latest Tertiary phase of valley deepening. Quaternary volcanism is characterized by stratovolcanoes, lava domes, cinder cones, and lava flows on the valley floors: these forms generally are affected by glacial erosion which was powerful at these latitudes. From a petrographic point of view, Quaternary volcanic rocks in central and southern Chile are basically andesite or basaltic andesite of the calc-alkaline series, whereas rhyolite is rarely found and true basalts are lacking. According to Vergara and Katsui (1969), these rocks originated by fractional crystallization from high alumina basaltic magma of the upper mantle, little contaminated by the sialic crust which is thinner here than in northern Chile (30 km instead of 60 km, according to Dragicevic, 1970). Pichler and Zeil (1972), however, do not share this opinion and assume that the Quaternary Andesite Formation in central and southern Chile, as in northern Chile, is a product of a primary andesitic magma originated by partial fusion of the lower crust.

In the Central Valley, between Santiago and Osorno (40° 35′ S) Quaternary deposits are composed exclusively of pyroclastics. Brüggen (1946), followed later by Karzulovic (1958 and 1963), interpreted them as morainic formations (*morrena de piedra pómez*). These deposits are especially well developed in the Santiago basin where they are emplaced in the topographically lower parts. Sections under a thick illuvial duricrust show a mass of generally nonstratified, poorly sorted ashes which also include pumice clasts. Borde (1957) was the first to reject the widely accepted hypothesis of glacial origin of these deposits, and he interpreted them as the result of an enormous and viscous volcanic mudflow of lahar type, produced by huge ash falls on the largely snow ice-covered high Andes. Subsequently, Borde's laharic explanation was favored by other Quaternary scientists (Segerstrom *et al.*, 1964; Tricart *et al.*, 1965) carrying out field investigations in the same area. Guest and Jones (1970), however, on the basis of peculiar "pipe" structures, reinterpreted these deposits as nonwelded rhyolitic ignimbrites of primary volcanic origin. Borde's views have been confirmed by Stiefel's (1968) sedimentological studies which brought out close similarities between Pleistocene ash deposits of the Santiago basin and the deposits left by lahars created by volcanic activity on snow-covered slopes

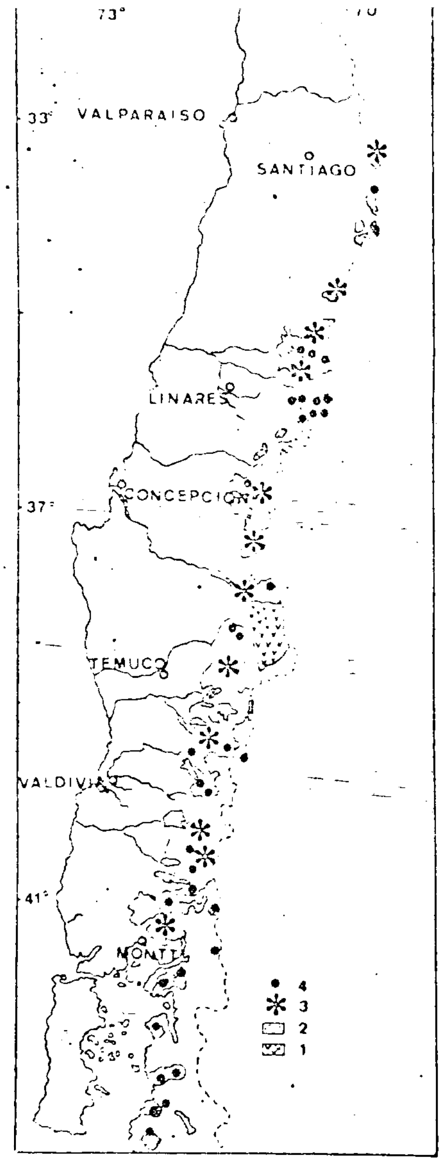


FIG. 6. Cenozoic volcanic areas in the Andean Cordillera in central and southern Chile, according to Pichler and Zeil (1972): (1) Pliocene andesitic to dacitic volcanic rocks; (2) Quaternary andesitic rocks; (3) active stratovolcano; (4) dormant stratovolcano.

[illegible] Villarica (39° 25' S) and Calbuco (41° [illegible]0' S) volcanoes in 1964. Consequently, [illegible] appears that an enormous lahar, induced [illegible]y a strong explosive eruption affecting [illegible]ither San José (33° 45' S) or, more prob[illegible]bly, Maipo Volcano (34° 10' S) during the [illegible]ext-to-last glaciation, is responsible for the [illegible]sh and pumice deposits whose remnants [illegible]re found today as far as the western [illegible]oot of the Coastal Range, not only in [illegible]he Santiago basin but also (Santana, 1971) [illegible]n the Rancagua basin (34° 10' S). It is not [illegible]nown whether the lahar was cold or hot at [illegible]he time of deposition. Other Quaternary [illegible]hars have been described farther south. [illegible]n exceptionally clear example is the Rio [illegible]eno lahar (34° 50' S) which flowed more [illegible]han 70 km from Planchón Volcano and [illegible]eft typical hummocky deposits (*cerillos* [illegible]*el Teno*); it appears to be late Pleisto[illegible]ene in age (MacPhail, 1973; Davidson, [illegible]974). The Rio Laja lahar (37° 15' S) studied [illegible]y MacPhail (1966) may be about 15,000 years old. No radiometric date is available for the probable upper Pleistocene lahar reported by Corvalán (1974) near Osorno.

On Tierra del Fuego Island three tephra [illegible]ayers, which represent very useful Holo[illegible]ene markers over a rather extensive area [illegible]n southernmost Chile and Argentina, have [illegible]een dated by Auer (1974): tephra I be[illegible]ween 9380 ± 90 and 8905 ± 110 years BP; [illegible]ephra II between 6600 ± 90 and 4480 ± 50 years BP; tephra III 2240 ± 60 years BP.

Antarctic Territory and Pacific Islands

Geologic studies dealing with Cenozoic volcanism have been carried out around the Chilean bases in Antarctica, mainly in South Shetland Archipelago (Gonzáles and Katsui, 1970). Pleistocene and Holocene volcanism account for the existence of Penguin Island (62° 06'–57° 56' S) which displays a characteristic circular form, and Decepción Island (62° 57' S–60° 30' W) which is a typical caldera drowned by the ocean (Roobol, 1973). Explosive activity which took place on Decepcion Island in 1967 considerably modified the previous topography. A new small island, called Yelcho Island, composed entirely of ash and scoriaceous debris was created near the northeastern shore of the inner bay (Fourcade, 1968; Clapperton, 1969; Baker *et al.*, 1969; Valenzuela *et al.*, 1970). As a consequence of a new eruption that occurred in 1970, Yelcho Island was connected to the main island (Gonzáles *et al.*, 1971; Baker and McReath, 1971; Shultz, 1972). There apparently are close petrographic similarities and eruptive synchronism between the South Shetland Islands and Antarctic Peninsula and the Andean region of South America (Gonzáles, 1972b).

New data concerning the Pacific volcanic islands under Chilean rule are now available. In Sala y Gómez (26°, 27' S–105°, 28' W) Fisher and Norris (1960) suspect that some olivine basalt on lava flows are probably Pleistocene. In Juan Fernández Archipelago, Robinson Crusoe Island (33° 40' S–78° 50' W) displays volcanic landforms that have experienced intense marine and subaerial erosion, and therefore would seem to indicate a late Tertiary age (Baker, 1967a). On Easter Island (27° 05' S–109° 20' W) well-preserved volcanic landforms points to recent eruptive activity. The three major volcanoes—Poike, a simple stratovolcano; Rano Kau with a caldera at its summit; Terevaka, the largest and the most complex—as well as little-weathered lava flows, appear to be Quaternary in age (Baker, 1967b). This hypothesis has been confirmed by recent K–Ar dates of 11 samples which are all younger than 0.5 million years (Gonzáles *et al.*, 1974). As expected, basalts are by far the dominant rock type, acid lavas being of very restricted development (Baker *et al.*, 1974).

ACKNOWLEDGMENTS

The bulk of the bibliographical material used for this report was compiled when the author was professor of physical geography at the University of Chile in Santiago (1962–1971). Additional material was collected in 1973 and 1976 during stays in Chile sponsored by the *Centre national de la recherche* *scientifique of France* (R.C.P. 339) and in 1974 during a visit to the Quaternary Research Center, University of Washington, on a 2-month scholarship granted by the Franco-American Commission for Educational Exchange. The friendly hospitality of A. L. Washburn, Director of the Quaternary Research Center, was highly appreciated. Critical comments on the report by S. C. Porter, Professor at the Department of Geological Sciences, University of Washington, are acknowledged with thanks. The author is also grateful to Miss L. Thornton who revised the English version of the report and to Miss B. Cowley who typed the manuscript.

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