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Neotectonics and Late Quaternary Marine Terraces along the Coastal Zone of the Northern Chile.

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칠레 북부해안에 발달된 제 4기 해안단구 (고해수면)와 신구조운동

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要 約

칠레 북부 해안에는 여러개의 해안 단구들이 발견되는데 이는 지구조 운동과 함께 해수면변동과 밀접한 관련이 있다. 단구의 형성 시기는 전부 밝혀 지지는 않았으며 여전히 논란이 되고 있다. 안토파가스타에서 이끼케까지 9개지역에서 발견되는 여러 단구에 대한 탄소 연대측정, 전자스핀 공명법, 우라늄측정, 아미노산 연대 측정 방법들을 이용하여 그 형성시기를 측정하였다. 그 결과들은 기본적으로 3~4개의 뚜렷한 단구를 선정하여 지역간에 서로 대비하였다. 대부분의 단구들은 산소 동위원소 연대 (O*x*ygen Isotope Stage) 3에서 11범주에 들어가는데, 이것은 계단식 단구들이 단지 지구조 운동만으로 형성된 것이 아니라 전지구 기후변동과 밀접하게 관련된 전세계 해수면변동에 의해 강한 영향을 받았음을 시사한다. 특히 플라이스토세에 형성된 일련의 해빈 사구들은 플라이스토세 초기에서 중기사이 반복된 간빙기를 나타낸다.

ABSTRACT

The northern coastal part of Chile is composed of several Quaternary marine terraces along the coastal areas. The uplift of high terraces is definitely related to tectonic activities and sea-level changes. The ages of some terraces are still unsolved and controversial, but many terraces are chronologically defined by analysis of ^{14}C, ESR, U/Th, and aminoacid racemization. The multiple terraces from nine localities from the south of Antofagasta to Iquique are observed. Basically, three to four conspicuous marine terraces are dated and correlated with each other. Most of the terraces are related to *Oxygen* Isotope Stages 3 to 11. This means that emerged staired terraces are controlled not only by tectonic uplifts, but also by sea-level changes, which are eventually affected by global climatic fluctuations. In particular, the outstanding preservation of Pleistocene beach-ridge series in the Mejillones Peninsula indicates the continuous history of regional tectonic uplifts and early to middle Pleistocene interglacials.

INTRODUCTION

The purpose of this paper is to review the history of Quaternary geology in the northern Chile in which the area is tectonically one of the most dynamic regions in the world due to the active subduction. Therefore, the several sequences of Quaternary deposits had been formed as a result of high stand sea events with respect of multiple transgressions. This paper is produced from the field trip which is led by L. Ortileb in November 23-25, 1995 after the 2nd annual meeting of IGCP 367 Project in which theme is "late Quaternary records of rapid change : application to present and future conditions". This paper is written on the basis of the field observation by the authors and some modification of the fieldguide book compiled by Ortlieb (1995).

Ten localities from the south of Antofagasta to Tocopilla (to the north) are mentioned in this paper. All areas were observed by the first author during the field trip. The nine localities are: 1) the Caleta Colosa terraces in the southernmost part of Antofagasta Bay and alluvial deposits at the mouth of Quebrada Jorgillo Bay; 2) Antofagasta terraces; 3) Salar Del Carmen Fault; 4) La Portada terraces; 5) La Rinconada terraces; 6) The Juan Lopez terraces; 7) Mejillones Peninsula beach-ridge series; 8) Hornitos and Chacaya terraces; and 9) Michilla terraces. All areas are shown in Fig. 1.

THE GEOGRAPHIC AND GEOLOGIC BACKGROUND

Geographically, Chile is a long, narrow country on the west coast of South America. It is over 10 times as long as it is wide, and stretches about 4,265 km from Peru in the north to the southern tip of the South American continent. Also, the northern part of Chile is one of the most arid area in the world. The average width of coastal plain is only about one to two km parallel to north–south. Six geomorphic characteristics can be chiefly divided from the coastlines to the inland (from the west to the east) (Fig. 1 and 2). They are 1) discontinuous and narrow coastal plains, 2) the Coastal Scarp, 3) the Cordillera de la Costa, 4) the intermediate depression (including Pampa del Tamarugal), 5) the Precordillera, and finally 6) the Andes Cordillera with the Altiplano (Fig. 2).

The maximum width is about 15 km occurred in the Mejillones Peninsula. In general, the elevation of the coastal plain is less than 300 m. The formation of this coastal plain is due to the sequential transgressions during the Quaternary Period. To the latitude of 20°S, the coastal plain merges into the north of Iquique. The Coastal Scarp, located from Arica at the boundary with Peru (18°S) to Taltal (25° 30'S). The elevation of this region is about 700 m. But, the northern part of the Coastal Scarp is much steeper and higher (about 1,000 m) than in the Antofagasta region and to the south. The Coastal Cordillera is a continuous longitudinal mountain range, running parallel to the coastlines. The width of this region ranges from a few km to about 50 km, and the maximum elevation can be about 2,000 m asl (above sea level). The Coastal Cordillera from Tocopilla to Antofagasta comprises thick Jurassic volcanic rocks to volcanogenic sedimentary rocks called La Negra Formation. The intermediate depression is composed of wide "pampas". The size of Pampa de Tamarugal is about 200 km long (from the north to the south) and about 40 km wide (from the west to the east). The elevation of this region is about 1,000 m asl. The Precordillera contains various geologic sequences in the mountain ranges with the maximum elevation of about 4,000 m. Along the east of the mountain ranges, the depression, filled with evaporites, is called "Salar de Atacama". The width of this basin is about 85 km at the elevation of 2,400 m. Finally, the easternmost region, the Andes Cordillera, is the highest elevation in the northern Chile. The Andes Cordillera, which is mostly the volcanic cone, is formed very recently. At the elevation of 4,000 m, the flat Chilean Altiplano is connected to the east of the water divide.

The climate of this region is very arid with almost no precipitation in decades. The average precipitation in the northern Chile is only about 10 mm per year. The Atacama Desert is the most arid area in the world. If it rains, it is very scarce with less than a few cm at most. This extreme arid conditions are due to the combination of atmospheric, oceanographic, and orogenic events. The humid air mass, coming from the Atlantic and Amazonian areas cannot pass over the Andes Cordillera (4,000–5,000 m high). Also, the cold Humbolt Current and related upwelling as well as the southeastern Pacific anticyclonic cell prevents the Pacific–side sea water from evaporating.

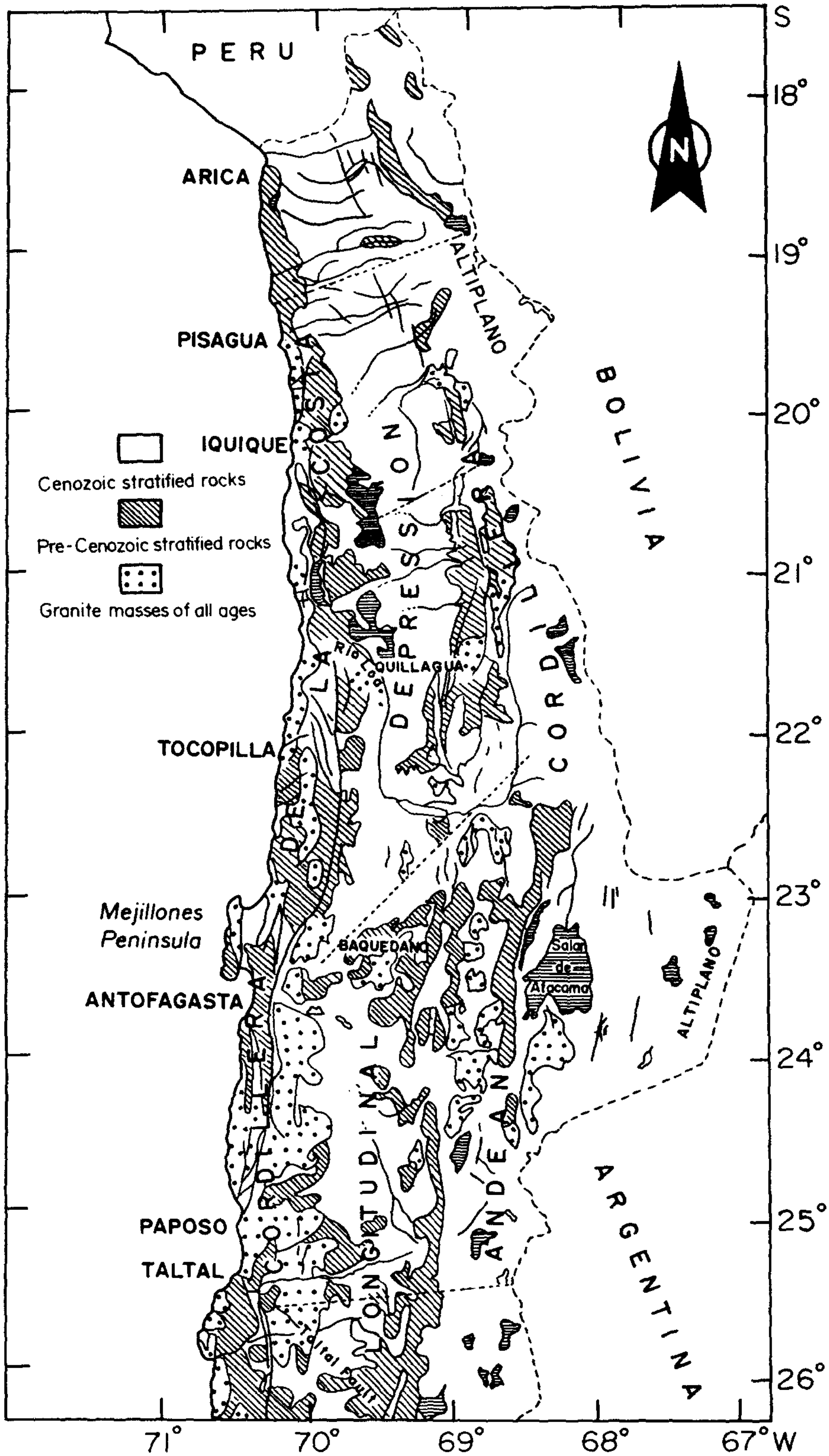

Fig. 1. The general geologic map from Taltal to Arica in the northern Chile(from Mortimer and Saric, 1977)

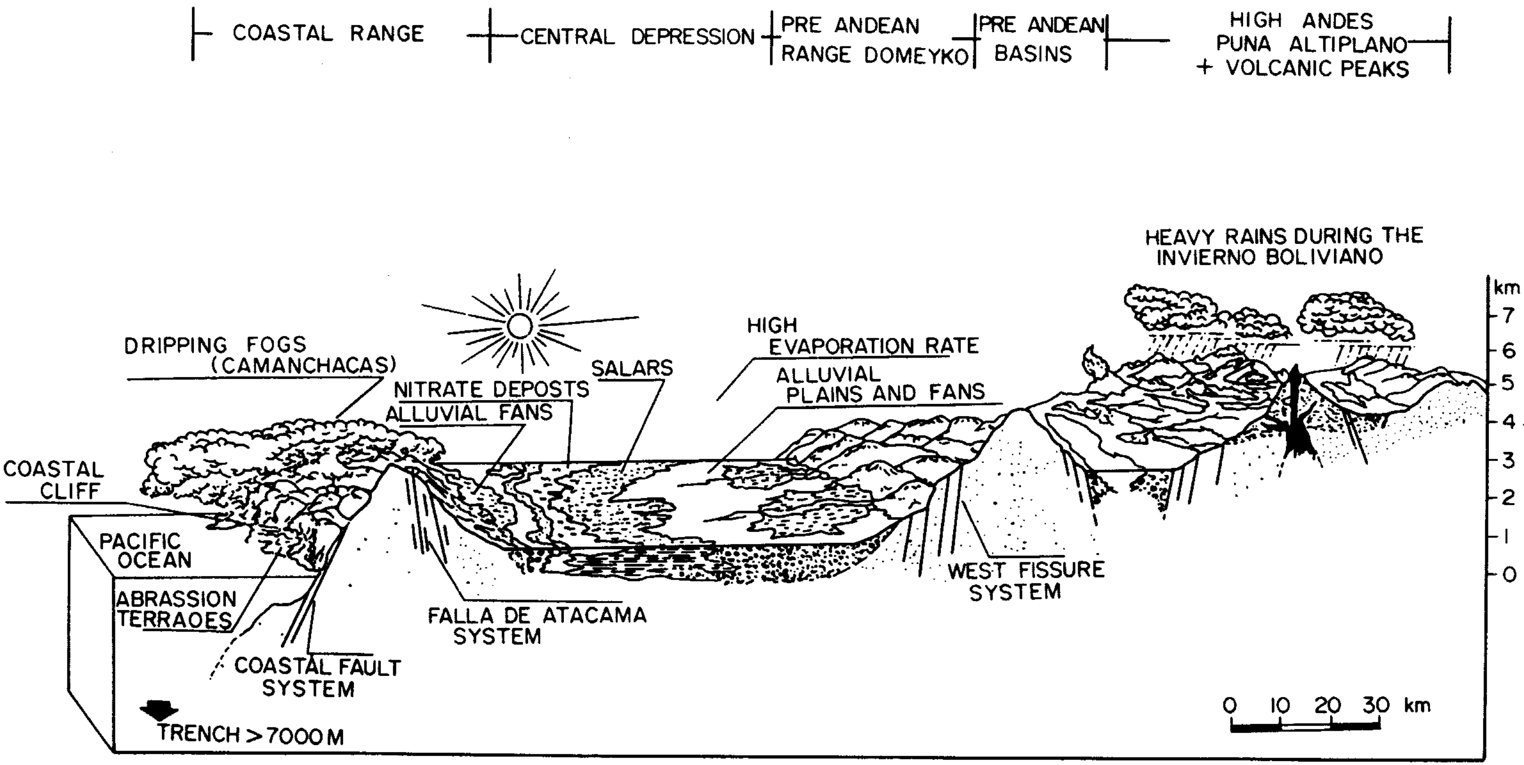

Fig. 2. The 3-D sketch of northern part of Chile, showing geomorphic characteristics. Six significant divisions of geomorphology are shown: 1) coastal plains; 2) the coastal scarp; 3) the Cordillera de la Coasta; 4) intermediate depression; 5) the Precordillera; and 6) the Andes Cordillera with the Altiplano (modified from Chong, 1988).

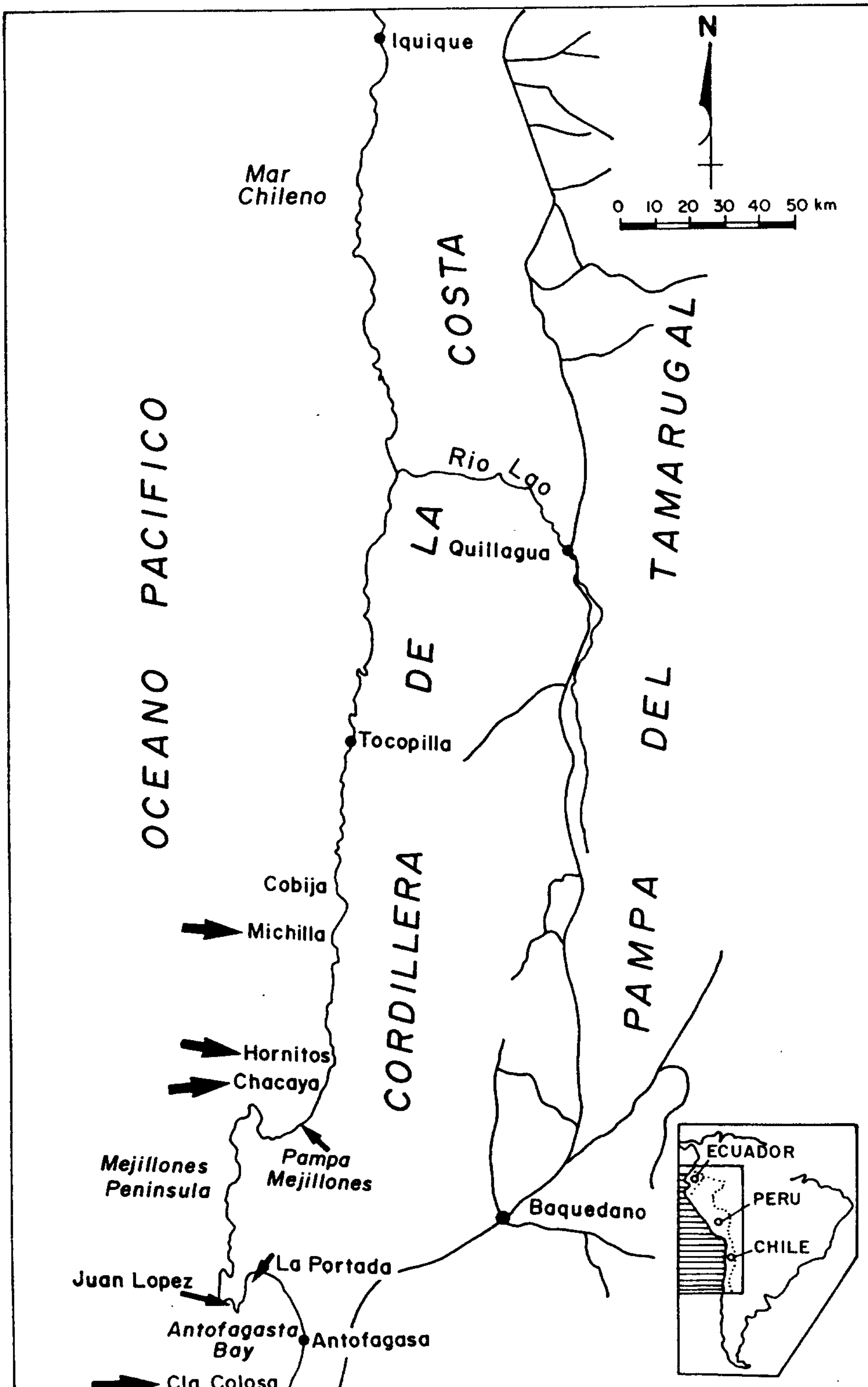

Fig. 3. The map of northern Chile. The black arrows show the localities of staired terraces during the field trip. The numbers are in order from the south: 1) Caleta Colosa in the southernmost part of the bay of Antofagasta (San Jorge Bay).

Most of the vegetation of the northern chile (called the Norte Grande) is xerophytic plants. The cactus and tillandsias even cannot survive in the coastal desert of northern Chile. However, a few cactuses are found at an altitude of about 500 m at the edge of the Cordillera de la Costa. A few species of trees grow in the pampa of the intermediate depression, including Salar de Atacama. These species are *Prosopis tamarugo* (tamarugo), *P. chilensis* (algarrobo), and *Guffroea decorticans* (chanar). The Atacama Desert contains the least number of species of terrestrial fauna in the world.

The active plate boundary is important in affecting the geomorphic features of the northern Chile as well as the entire South American continent. The subduction of the Nazca plate underneath the west of the South America Plate is a main cause of the uplifts of Chilean coasts. Occasional earthquakes occur in the area of the colliding part of these two plates. In July, 1995, the most recent earthquake (Ms 7.3) caused 4 causalities and destructions of Antofagasta areas. The deepest part of the Chile–Peru Trench is located near Antofagasta (about 8,000 m). Offshore Antofagasta, an aseismic ridge is located parallel to the Nazca Ridge.

COLOSA PLEISTOCENE MARINE TERRACES

Caleta Colosa is located in the southernmost part of Antofagasta Bay (Fig. 3), and comprises three Pleistocene terraces (Fig. 4). The highest and oldest terrace lies at about 70 m above mean sea level, and is believed to be formed as a result of a Pliocene transgression (Martinez and Niemeyer, 1982). The second highest one is located at about 30 m asl near the mouth of Quebrada Jorgillo (Fig. 4). The age of the second terrace is uncertain even though several dating methods such as ESR and U/Th analyses were used from mollusca shells (Radtke, 1989). The

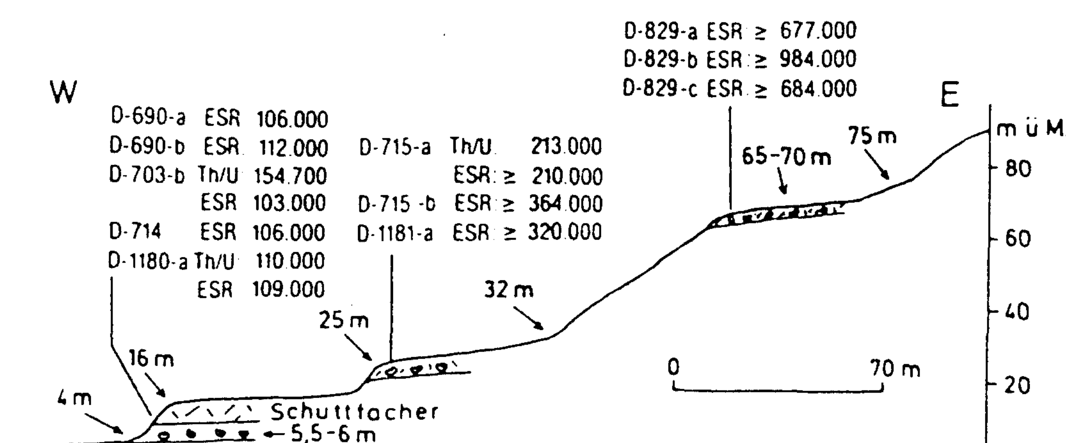

Fig. 4. Geochronological data from the three Colosa Pleistocene terraces, using by ESR(Electron Spin Resonance) and U–series (Radtke, 1989).

youngest and lowest terrace which is also believed to be marine is found at the same location of the second terrace. The age of this youngest terrace is formed during the last stage of interglacier based on ESR and U−series (Fig. 4). This age was confirmed by another analysis of U−series and amino−acid racemization (Ortileb et al., 1993). Therefore, the 30−ka B.P. dating on this youngest terrace done by Paskoff (1973) was discarded and accepted as the last interglacial highest sea−level stand (Isotopic Substage 5e, 125 ka).

LATE QUATERNARY ALLUVIAL SEQUENCES AT QUEBRADA JORGILLO BAY

At the mouth of Quebrada Jorgillo, alluvial sediments during the Holocene are deposited underlain by the marine terrace sediments, either associated with the 5e stage or above the wave−cut abrasion surface of the Oxygen Isotope Stage 5e sediments. These alluvial sequences are important to mark the chronological line between the Holocene and the pre−Holocene time. The alluvial sequences are part of alluvial fan systems and built at the foot of the coastal escarpment. Three units are distinguished in these sequences based on sedimentological characteristics.

The floods of Quebrada Jorgillo dissect the alluvial sequence along the Coloso embayment. To the north, reddish mudflow and debris−flow deposits are originated from the Caleta Coloso Formation. To the south, the intercalation of tan alluvial and fluvial units is found and is originated from Bolfin Formation which is composed of the metamorphic and intrusive gray substrate. However, the observation during this field trip has brought some questions of fluvial deposits because some sedimentary structures are shown more likely to be marine deposits (probably beach deposits). The formation of fluvial deposits is interpreted as a result of washover of a large watershed of the Cordillera de la Costa (about 40 ㎢), while the debris flows were moved from a much shorter distance from smaller watersheds. In the northern part, several units of alluvial deposits are identified, indicating fluctuations of climatic changes such as repetitions of arid and semi−arid conditions, indicating the last glacial/interglacial cycles.

PLIOCENE ANTOFAGASTA TERRACE

The age of the highest terrace, also called "the Antofagasta Terrace", at about 100 m asl in Antofagasta was distributed to the Pliocene (Martinez and Niemeyer, 1982). The flat but slightly seaward−dipping erosional surface is found from the Quebradas Salar del Carmen to La Negras and is several 100 m in width. The materials for the age−dating are merely mollusca shells. Among them, the diagnostic species of the Pliocene are *Chlamys vidali* and/or *Chlamys hupeanus*, and *Concholepas* cf. *nodosa*. The sedimentary unit is very similar to that of the La Portada Fm at La Portada locality which will be mentioned later. The age of sedimentary unit at Coviefi locality (at 90m asl) is inferred to be Pliocene based on ashes (correlated with the outcrop dated as 3m.a. old ; Naranjo, 1987). Some upper units do not contain the diagnostic species of Pliocene mollusca such as *Chlamys*. And some fragments of shells *(Concholepas)* are similar to Pleistocene–Holocene species *(C. concholepas)*. Therefore, this unit may be correlated to a Pleistocene marine unit underlain by the Pliocene sediments. Even though the age of the Antofagasta Terrace is still controversial, this terrace was cut by the Pliocene high seastand and probably another transgression occurred during the early to early middle Pleistocene. This new view of the ages in the Antofagasta Terrace implies neotectonic interpretation. If the sea level during the early Pleistocene was the present level, the inferred mean uplift rate of this terrace can be calculated to be about 100mm/10^3yrs (100m uplift in 10^6 yr $\pm 30^5$). Regardless of the determination of true age in the remnants of the Pleistocene transgression, the new chronology suggests that this terrace be more rapidly uplifted than previously conceived.

SALAR DEL CARMEN FAULT OF ATACAMA FAULT ZONE(AFZ)

The escarpment of the Salar del Carmen Fault which is part of the Atacama Fault Zone (AFZ) can be observed from the road of Antofagasta to the Panamerican Highway (Fig. 5). The elevation of this escarpment is a few m, and there is no evidence of strong erosion. The age of this escarpment might be the Holocene to late Pleistocene even though the age of the last activity on the AFZ is still in discussion. Probably, the last movement of this fault might be as old as the late Middle Pleistocene (150 to 500 ka). The AFZ is about 1,100 km long and oriented to north–south between Iquique (20° 30' S) and La Serena (29° 30' S) (Fig. 5). It is located along the eastern flank of the Cordillera de la Costa. Within the AFZ, two segments are divided by the NW–SE oriented Taltal Fault (Fig. 5). Many authors studied the characters and age of the AFZ. Among them, St. Amand and Allen (1960) were the first ones to study the AFZ. They divided the AFZ into two sectors (one is between Iquique and Taltal, and the other is between Taltal and La Serena). They considered the Atacama Fault System as a single strike–slip motion one. Bowes et al. (1961) modified that the two sectors have moved in opposite directions with two distinctive strike–slips. Arabasz (1968, 1971) is the first one to consider that the AFZ is the one single fault with a strong strike–slip motion during the early Mesozoic, and was changed into dip–slip in the Quaternary Period. He could not distinguish microseismicity associated to the recent motions. Scheubur (1987) studied more in detail to define two stages of sinistral strike–slip in the Mesozoic from the sector north of Paposo. One occurred during the late Jurassic and the other is in the early Cretaceous. He also observed that the AFZ has been motioned again by dip–slip in the late Miocene, causing the uplift of the western block. The last two motions were dated as 144–131 ma. and 19–5.5 ma. from the radiometric method (Herve, 1987a, 1987b),

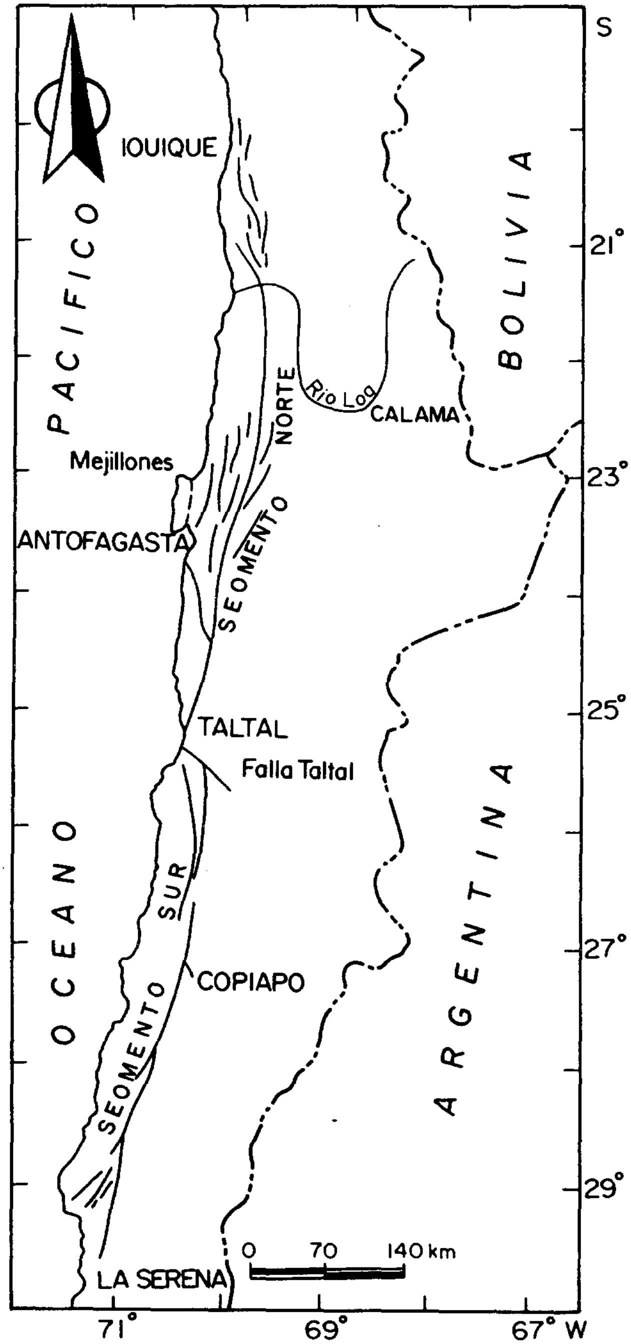

Fig. 5. The Taltal Fault divided the Atacama Fault Zone into two segments, called Segmento Norte and Segmento Sur (from Herve and Thiele, 1987).

suggesting that the last movement of the AFZ would have occurred during the Miocene. The more precise age of the last activity of this dip-slip fault was determined as the prior to the late Miocene (the more precision might be the late middle Miocene) by Naranjo (1987). He suggested that the recent activity of the AFZ would be due to gravitational collapse related to hydrological changes. Recently, Armijo and Thiele (1990) speculated that the AFZ be moved as a left-lateral strike-slip motion during the Quaternary, but this statement is merely based on the observation of offsets on alluvial fans north of Salar del Carmen.

PLIOCENE LA PORTADA FORMATION AND OTHER CENOZOIC FORMATIONS

Most of these formations are found in the outcrops of the Mejillones Peninsula and at Hornitos (Fig. 1). The La Portada Formation is about 40m thick, and is characterized by yellowish shelly sandstone, which is unconformably underlain by the Jurassic La Negra Fm (Table 1 and Fig. 6). The picture was taken in the seacliff of La Portada in front of Jorge Bay. As seen in the picture (Fig. 6), five formations are recognized: 1) the Jurassic La Negra Fm; 2) the Pliocene La Portada Fm; 3) the 300 ka marine deposits; 4) reworked alluvial deposits; and 5) the Holocene dunes. The whole sequence is interpreted as a shallow nearshore unit with shoreface and foreshore facies at the base. This formation is overlain by marine Pleistocene sand terrace dated as about 300 ka(Isotopic Stage 9). Near the top of this terrace, reworked alluvial deposits are found in interstratified layers. The Holocene dunes, at the topmost part of the sequences, are developed at the edge of the seacliff. The La Portada Fm was considered as the Mio-Pliocene marine complex (Ferraris and Biase, 1978), but the fauna of *Chlamys vidali* indicates that this formation be the late Pliocene (Martinex and Niemeyer, 1982). The three formations are successively identified: The marine Caleta Herradura Fm with the age of the Miocene (Krebs *et al.*, 1992), the La Portada Fm of the Pliocene, and the Mejillones Fm of the Pleistocene (Ferraris and Biase, 1978; Flint *et al.*, 1991; Hartley and Jolley, 1995) (Fig. 6). The age datings were conducted for the middle Pleistocene (about 300 ka) marine terrace. The analysis of amino-acid racemization and U-series on the shells of *Mulinia* cf *M. edulis* and *Mesodesma donacium* are shown in Table 2.

FAULTED MIDDLE PLEISTOCENE MARINE TERRACES IN THE SOUTHERN MEJILLONES PENINSULA

In the northern part of the the Antofagasta Bay (from Las Lozas to La Rinconada), cemented Pleistocene sandstone units underlain by the Pliocene substrate were tilted toward the west. Crustal faults, mostly activated during the Holocene Epoch, separate an semi-graben in the east from the uplifted Cerro Moreno block. In the cliff, an offset fault was uplifted about a maximum of 6m (Armijo and Thiele, 1990). This offset is more ex-

Table 1. Stratigraphy of the Mejillones Peninsula region (modified from Hartley and Jolley, 1994)

AGE (m. a.)	ERA	STRATIGRAPHY	LITHOLOGY	THICKNESS (m)
0.1	Holocene	Mejillones Fm and equivalents	alluvium	25 – 50
	Pleistocene		shallow marine deposits	80
1.64	? ? ? Pliocene	? ? ? Laportada Fm and equivalents	shallow marine deposits	40
5.2	Miocene	Caleta Herradura Fm	shallow marine deposits	160 and more
Jurassic volcanics, granitoids and Cretaceous sediments				

Table 2. The geochronological results by aminoacid racemization and U-series in the 300 ka marine deposits of the southern Mejillones Peninsula (Ortlieb, 1995)

sample no.	elevation asl (m)	mollusca	method
C92-38	+ 28	Mulinia cf. M. edulis	A/I:0.66±0.10 (n=12)
C92-38	+ 28	Mesodesma donacium	A/I 0.67±0.12 (n=11)
C92-39	+ 28	Mulinia cf M. edulis	U/Th:282±9 ka
C92-39	+ 28	Mesodesma donacium	U/Th:275±11 ka, 288±12 ka

Fig. 6. The geological deposits in the La Portada sea cliff (photographed by Yi, 1995). The formations are deposited in order from the bottom to the top: 1) the Jurassic La Negra Formation (Fm); 2) the Pliocene La Portada Fm; 3) the middle Pleistocene marine terrace deposits; 4) the upper to upper middle Pleistocene alluvial deposits; and finally 5) the Holocene eolian sand dunes. See Table 1 for stratigraphic relations.

Fig. 7. The conspicuous surficial fractures and slidings at the sea cliff of La Portada due to the earthquake occurred on July 30, 1995 (photographed by Yi, 1995).

posed due to the downcliff sliding by the 1995 earthquake (Fig. 7). These kinds of normal faults are part of a complex en echelon system, associated with NNW-SSW and N-S fractures.

EFFECT OF EARTHQUAKES : THE 1995 ANTOFAGASTA EARTHQUAKE

On July 30, 1995, the Ms 7.3 earthquake in Antofagasta caused three deaths and some vertical movements. The fractures on the surface and gravity sliding on the seacliffs of the northern Antofagasta Bay were noticed (Fig. 7). But no major faults were created by this earthquake.

SEQUENCES OF EMERGED BEACH RIDGES IN THE MEJILLONES PENINSULA

The series of well-preserved beach ridges related to neotectonic uplifts is shown in the northern and southern part of the Mejillones Peninsula (Fig. 8). These beach ridges are extended from the present coastal cliff to an elevation of 200 m asl. The whole emerged beach ridges are parallel to the present coastlines and contain the beach characteristics such as cusps, indicating that the whole coastal plain has been uplifted without major internal deformation. The age of these former beach ridges and time-interval of beach ridge processes are not clearly determined yet. The marine terrace cut by the seacliff is assumed as Isotope Stage 9 (ca. 300 ka). At about 200 m asl in the north of the beach-ridge sequence, the Pliocene marine units are found by the correlation of marine fauna. The youngest terrace, representing the Pleistocene transgression is also found at about 50 m former seacliffs to N, NE and E of the Antofagasta Airport. The above characteristics indicate that the time lapse of the beach-ridge formation can be several hundred thousand years.

The series of beach-ridges in the northern part of the Mejillones Peninsula, called Pampa Mejillones is about 20 km long (from N to S), and about 10-20**km** wide (from W to E). These ridges are encompassed by the large fault scarp to the west and the Cordillera de la Costa to the east (Fig. 8). The highest ridges to the south in this region is about 220 m asl, and the most recent ones are located in about 10-20 m seacliff to the north. The sequence of beach ridges, which are subparallel to the present coastlines, is fully filled in this plain (the former Majillones Bay). The beach-ridges in the northern part of this peninsula are much extended and well-preserved than those in the southern part. The height of the beach ridges is about 1-2 m and the width of them ranges from 50 to 200 m. Each one is separated from one another. The beach-ridges are characterized by shelly sands with some well-rounded beach pebbles. The terrace at an elevation of 150 m asl containing the warm-water fauna such as *Trachycardium procerum* is correlated to the terrace at La Rinconada, suggesting that shelly ridges at this elevation (150 - 160 m asl) is dated to the Isotope Stage 11.

Unfortunately, the complete chronostra-

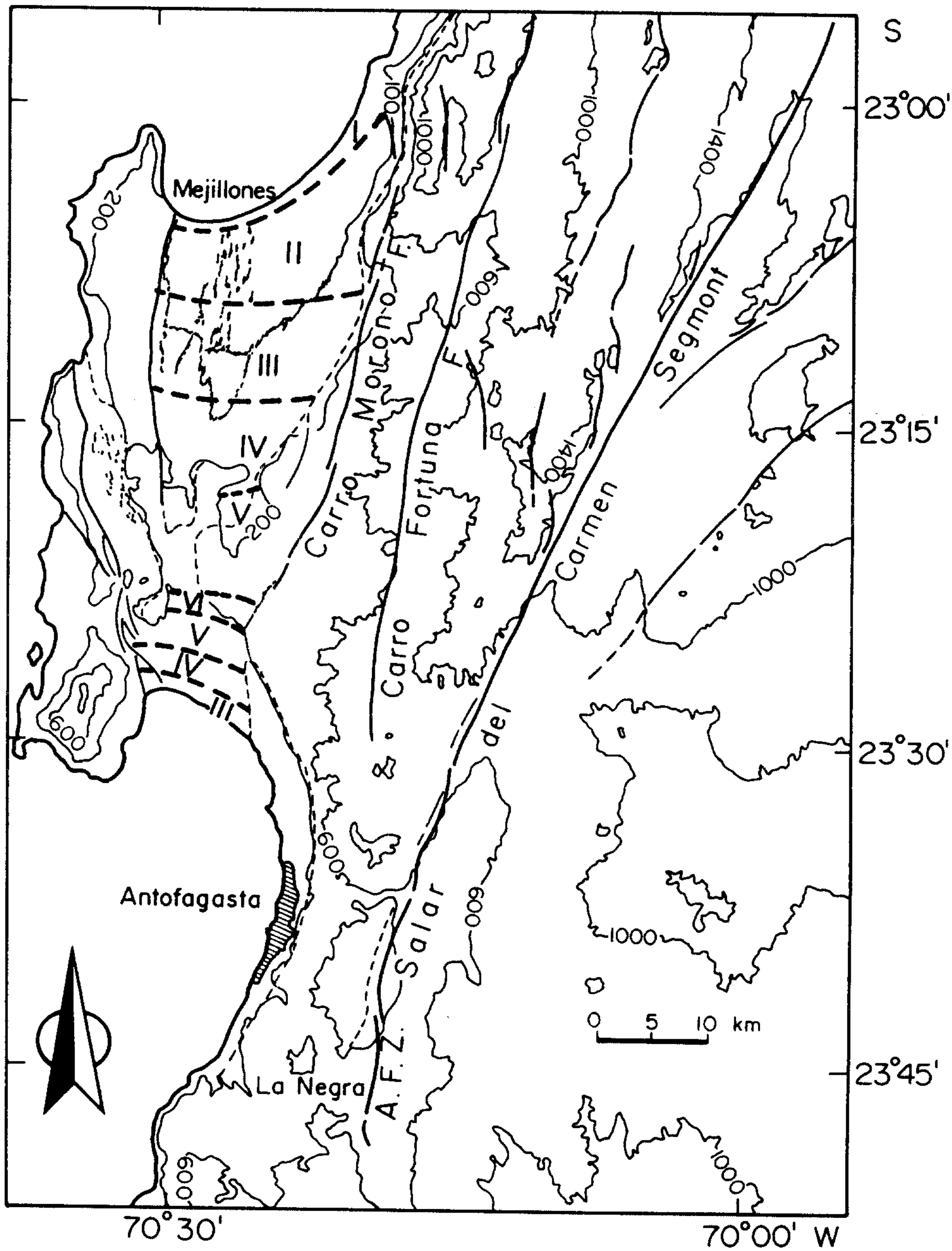

Fig. 8. The series of emerged beach-ridges in the southern and northern part of the Mejillones Peninsula. The large fault scarps cross to the west (from Armijo and Thiele, 1990).

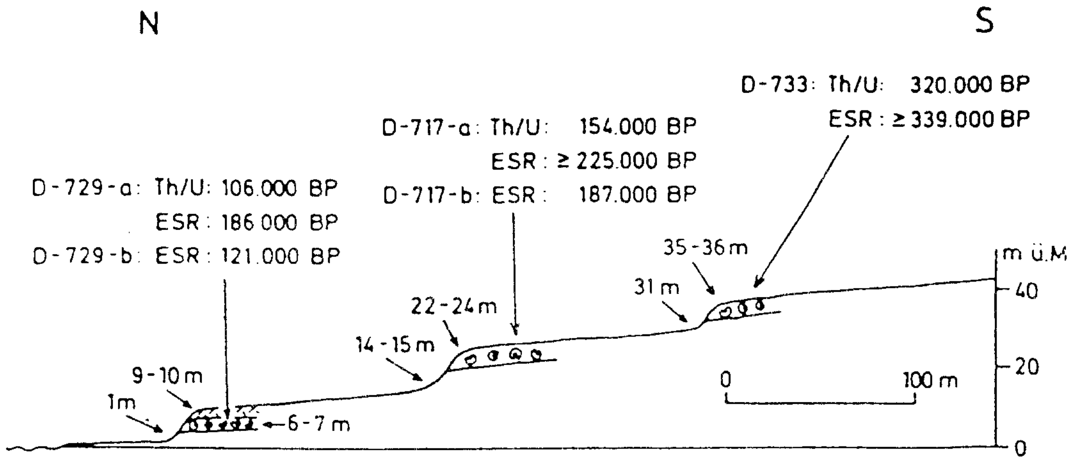

Fig. 9. Geochronological results on shell fossils from the three terraces at El Rincon(from Radtke, 1989).

Table 3. Dating of marine shells by aminoacid racemization from beach terraces of the Pampa Mejillones (from GEOTOP, unpulished)

Sample #	Elevation (m)	Mollusca Species	A/I	number of samples (n)	sigma	Isotope Stage
C92−36	+25	M. edulis	0.49	2	0.05	5e
C92−36	+25	V. antiqua	0.41	1		5c (?)
C−94−126	+70	M. edulis	0.55	3	0.03	7 (?)
C93−46	+110	P. thaca	0.83	3	0.04	?
C94−125	+110	M. edulis	0.78	3	0.08	?
C89−5	+120	P. thaca	0.78	2	0.06	?
C94−124	+130	M. edulis	0.85	2	0.11	?
C94−117	+160	P. thaca	0.92	2	0.08	11
C94−117	+160	V. antiqua	0.85	2	0.10	11 (?)

tigraphy of beach–ridge sequences is not determined yet. The several authors proposed the age of the beach–ridge formation (Herm, 1969; Okada, 1971; Ferraris and Di, 1978; Craig, 1988; Armijo and Thiele,1990; Ortlieb and Marchare, 1993; Ortlieb *et al.*, 1996 (in press)). Among these, the recent research (Ortlieb *et al.*, 1996 (in press)) is counted as the most reasonable interpretation based on the fauna and at an elevation of 150～200 m asl and correlation with the La Rinconada warm–water fauna, suggesting the Isotope Stage 11.

The age determination of the whole beach–ridge formation in the northern part of Antofagasta Bay and the southern part of Mejillones Bay was stated as Late Pleistocene (Armijo and Thiele, 1990). However, the recent study shows that most of them were formed during the Middle Pleistocene (Ortlieb and Marchare, 1993). The flat terrace (Marine Terrace I at about 400 m asl) of Cerro Brandurria was believed to be eroded during the early Pleistocene (Okada, 1971; Armijo and Thiele, 1990), but the Pliocene fauna on the Marine Terrace I make clear that the eroded time of this marine terrace is older. The uplift rates during the Quaternary are difficult in determining due to different age interpretations of terraces. It was proposed as 2,400mm/ ka (Armijo and Thiele, 1990), but Ortlieb et al (1995) recalculated as a mean rate of 100 – 200 mm/ ka in the Pampa del Aeropureto or Pampa Mejillones in the whole Quaternary Period.

The chronological data from shells on three staircased terraces of El Rincon at the NW edge of Pampa Mejillones suggest the last formation of beach–ridges of the Pampa Mejillones sequence (Fig. 9). The dating methods for these terraces are ESR, U/Th, and amino acid racemization. The results of these datings are shown in Table 3. The aminoacid datings of the vertical sequence are reasonably good, showing increasing ratios with the elevation of the localities. In Table 3, it is noted that A/I ratios in the Isotope Stage 11 which is correlated with the warm–water fauna are higher than in other localities (0.79 of A/I ratio at Chacaya, south of Hornitos; this locality will be mentioned later). Six marine terraces in the southern part of Mejillones Peninsula and five marine terraces in the Pampa Mejillones are recognized by Ortileb, Goy, and Zazo (prep). Marine Terrace I is corresponded to Isotope Stage 5, and Marine Terrace II to Isotope Stage 7. So the increasing number of Marine Terraces indicates older ages in response to 5, 7, 9, 11, etc.

MEJILLONES FAULT

The Mejillones Fault, the major crustal fault, offsets between the alluvial fans in the westernmost edge of Pampa Mejillones and the range of Morro Mejillones (Fig. 10). The activity of this fault occurred during most of Cenozoic Era. This fault acts as a boundary for the semi–graben of Pampa Mejillones, but this semi–graben itself is uplifted. It is chronologically difficult in correlating with Pleistocene marine units across the fault zone. The highest elevated unit of Pleistocene is lo-

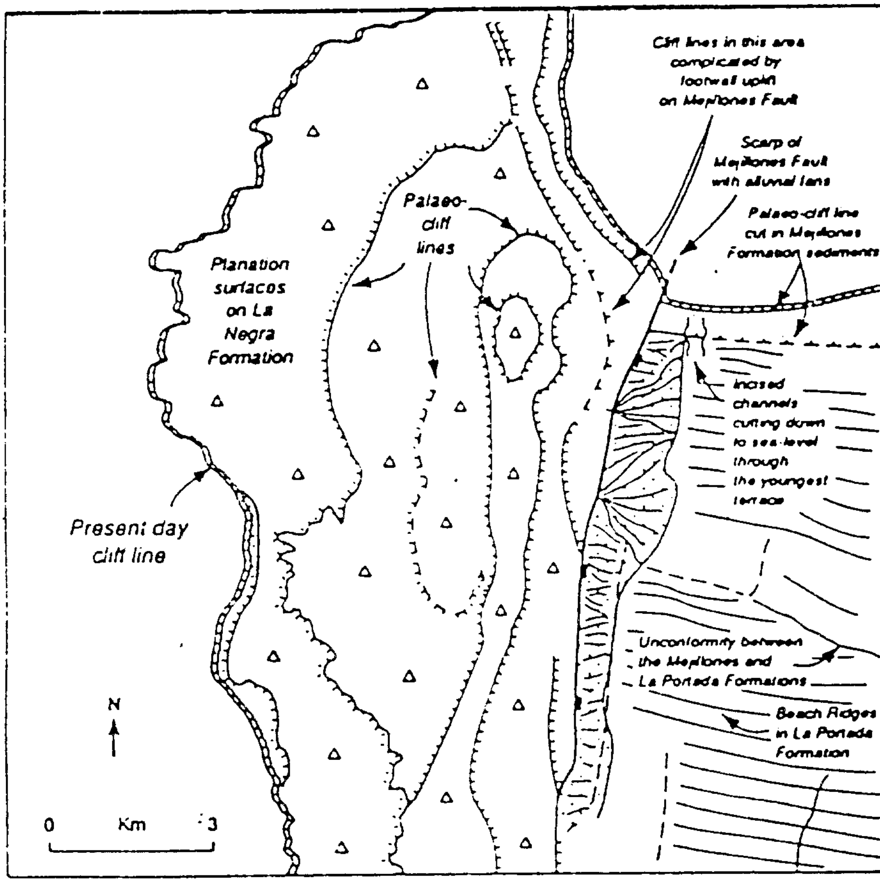

Fig. 10. The sketch map of the Morro Mejillones, showing the Mejillones Fault scarp and part of the beach ridges of Pampa Mejillones (from Hartley and Jolley, 1995).

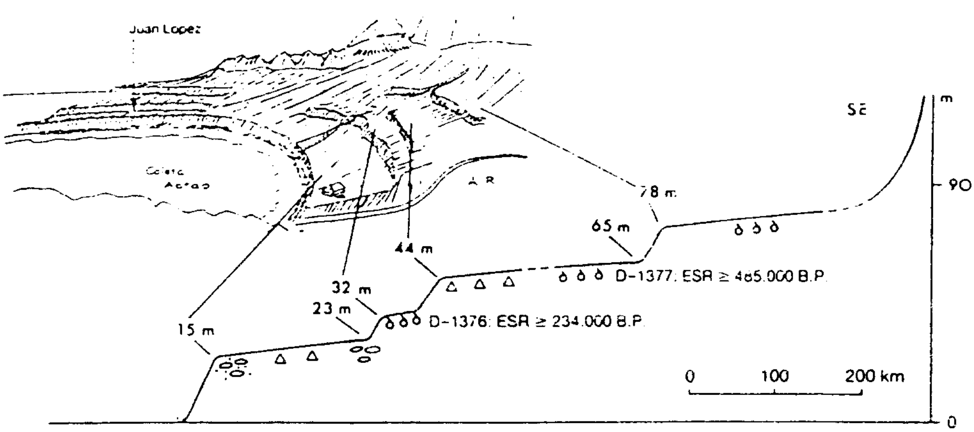

Fig. 11. The four conspicuous marine terraces near Juan Lopez (from Ratunsny and Radtka, 1988).

cated at 440 m asl on the uplifted block in the west. The minimum vertical offset of 220 m is found in the east of the fault in which age is inferred as 1−1.6 ma. It is surprising to holding intactly the series of well−preserved beach ridges during the last several hundred thousand years in spite of an active tectonics.

MARINE TERRACES IN THE JUAN LOPEZ AREA, THE SOUTHWESTERN MEJILLONES PENINSULA

Several marine terraces are found near the village of Juan Lopez. At least, three to four terraces up to about 150 m asl are conspicuously shown along Juan Lopez Bay. The four terraces at the inner edge contain 20 m, 35 m, 60 m, and >90 m asl in elevation, respectively, and the wave−cut plateforms are covered with nearshore sediments (mostly conglomerates and sandstones with some fossils). Fig. 11 shows three terraces on the northwestern coast of Abtao Bay near Juan Lopez. The ages of Isotope Stages 7 and 9 are resulted from ESR method (Ratusny and Radtke, 1988). Unfortunately, the geochronological results done by ESR and U−series on the three main terraces near the Bay of Abtado do not give solid age configurations (Fig. 12, Radtke, 1989).

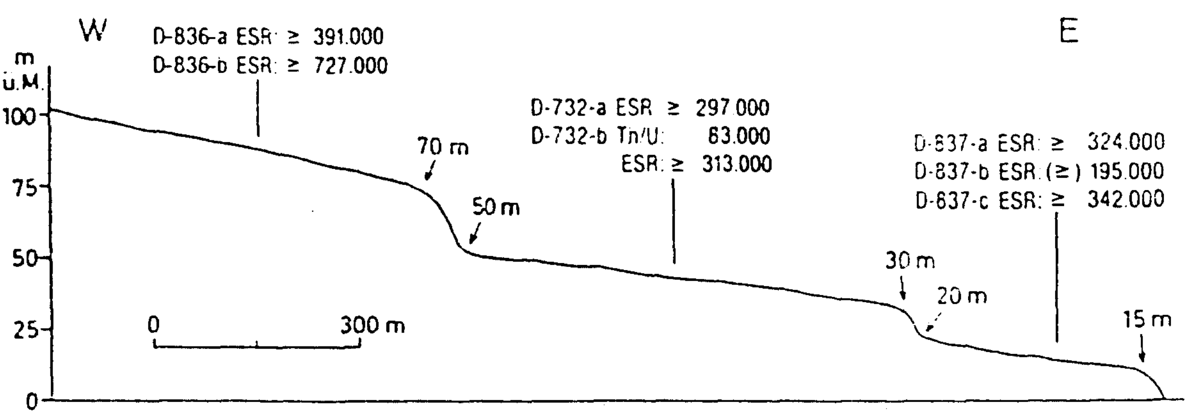

Fig. 12. The results of ESR and U−series datings of shell fossils on the three marine terraces near Bay of Abtao (from Radtke, 1989).

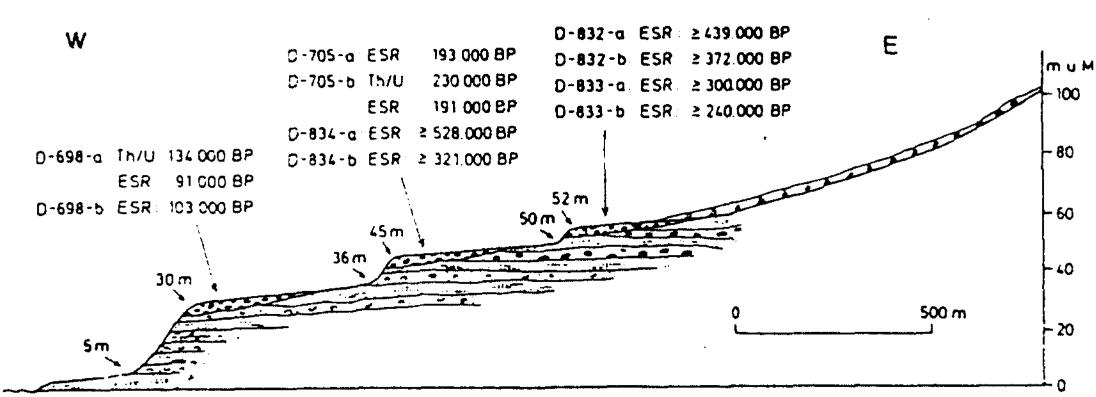

Fig. 13. Geochronolgical data from three marine terraces of Hornitos (from Radtke, 1989).

SEQUENCE OF HORNITOS AND CHACAYA MARINE TERRACES : CA. 300 KA

The aminoacid racemization and U–series datings provide more detailed chronological and morphological correlations at the three Hornitos marine terraces (Fig. 13 and Table 4). The lowest terrace was dated as the Isotope Substage 5e, the second the Isotope Stage 7, and the highest one the Isotope Stage 9 (Ortlieb *et al.,* 1994). Also, the substantial dates of U–series (from 15 samples) and aminoacid racemization (from 115 samples) make possible the detailed chronological correlation of marine terraces. The A/I ratios of *Mulinia edulis, Mesodesma donacium* and *Protothaca thaca* suggested the Isotope Substage 5c from the A/I values of 0.36–0.42, the Isotope Substage 5e, 049–0.51, the Isotope Stage 7, 0.61–0.65, the Isotope Stage 9, 0.69–0.73, and the Isotope Stage 11, 0.80, respectively (Table 4). The U–series is important in determining the absolute dates in this area. The correlations between the A/I ratio and the U–series are as follows (Table 4): 103 to 109 ka on the top of the Holocene seacliff, at 18 to 25m asl as the Isotope Substage 5c. The U–series of 116/124 ka and A/I ratios of 0.50 is assigned to the Isotope Substage 5e age. The 36 m asl elevation of the inner edge of the low terrace records the Isotope Substage 5e with the mean uplift rate of 240mm/ka. If we consider that the Isotope Substage 5c terrace at 25 m asl was uplifted constantly through time, the paleo–sealevel would have been close to the present level (no more than 10 m below). The next higher marine terrace, the least conspicuous and the narrowest one, contains 50~63 m asl to the east and north–east of Hornitos but higher to the south. Two high seastands, the Isotope Substages 7a and 7c, were found based on some A/I ratios and one U–series analysis. The third higher terrace is wide (the widest at the east of Hornitos) and higher than 80 m asl in elevation, particularly at the inner edge of terraces hidden by the alluvial fans at the foot of the Coastal Cordillera. Some A/I ratios (mean values of 0.73 for *P. thaca,* 0.71 for *M. edulis,* 0.69 for *M. donacium,* 0.70 for *Venus antiqua*) provide the Isotope Stage 9 (ca. 330 ka) in this locality of 75m asl elevation (Table 4). The Isotope Stage 11 was supported by the A/I ratios of 0. 70 for *P. thaca* at Hornitos. This terrace, lacking the warm–water fauna, is correlated with the marine eroded surface at the northern end of Antofagasta Bay (La Portada). At La Portada of the Mejillones Peninsula, this terrace is dated as 280–290 ka by the U–series from *Trachycardium procerum* (Guzman *et al.,* 1995; Ortieb, 1996(in press)). The oldest terrace of 170 m asl in elevation at the east of Chacaya is considered as the higher

Table 4. Chronostratigraphic data analyzed by aminoacid racemization and U-series on mollusca shells from the marine terrace deposits at Hornitos and Chacaya (south of Hornitos) (GEOTOP, unpublished).

Sample	Elevation (m)	Species (number)	A/I ratio	U/Th TIMS	U/Th	Isotope Stage
			Hornitos (Locality 1)			
C92-6	+ 25	P. thaca(3)	0.36	105.3(1.0		5c?
		M. edulis(2)	0.42	108.3(0.8		
		E. rufa(1)	0.38	108.8(1.0		
C92-10	+ 18	P. thaca(2)	0.49	106.1(0.8	124(7.0	5e?
C92-10				109.2(0.9	116(6.0	
					106(5.0	
					119(5.0	
C92-11	+ 18	M. edulis(4)	0.51		5e?	
C93-83	+ 60	M. edulis(3)	0.63			7
C93-83		M. donacium (3)				
C93-80	+ 75	M. edulis(3)	0.71			9
		P. thaca(3)	0.73			
		M. donacium (3)	0.69			
			0.70			
			Chacaya, south of Hornitos (Locality 2)			
C92-2	+ 23	M. edulis(3)	0.47			5e
		M. donacium (3)	0.46			
C94-108	+ 30	M. edulis(3)	0.45			5e
		M. donacium (3)	0.47			
		V. antiqua(3)				
			0.53			
C93-85	+ 100	P. thaca(2)	0.79			11?

Isotope Stage 11 age.

HOLOCENE MARINE TERRACE IN MICHILLA BAY

The Holocene terrace at the elevation of 6 m asl is found in the coast of Michilla Bay, which is the origin of the only Holocene terrace in the northern Chile. The sediment accumulation in this small embayment might be the reason to preserve this recent terrace. However, it is not still known for the formation of fossiliferous Holocene coastal sands and gravels at the foot of the old seacliff. There is no apparent tectonic uplift in this region. The age of this terrace is about 6,725±95 B.P. by ^{14}C dating (Leonard and Wehmiller, 1991). The mean A/I ratio of 0.16±0.03 is measured on three *Mulinia* shells from the same unit by the above authors. The confirmation of this age is done by Ortileb et al. (1994) using U-series analysis (7.1±0.1 and 7.2±0.2 ka). The age obtained from other places in the world, including the central Peru (Wells, 1988) also exhibits that the maximum of the Holocene seastand occurred at about 7,000 B.P.

Another locality in Michilla Bay shows the Isotope Stage 5 in the lower terrace at about 40 m asl in elevation, but it is hard to distinguish the Isotope Substages 5c and 5e from either aminoacid racemization or the U-series analyses. Aminostratigraphic data were analyzed from three terraces in the area of Michilla-Pta Tames (Leonard and Wehmiller, 1991). However, the geomorphostratigraphic units are divided into two plateforms which are probably of the Isotope Substages 5e and 5c ages, respectively.

CONCLUSIONS

1. Most of emerged staircased marine terraces along the northern coast of Chile are formed by the tectonic uplifts related to the subduction of the Nazca Plate in the Pacific side.

2. The marine terraces from several localities are well correlated with each other with respect to the Isotope Stages 3 to 11 (Fig. 14).

3. As seen in Fig. 14, five MTs (Marine Terraces) are recognized: a) MT 1 (late to late-middle Pleistocene) includes the terraces of La Portada, Mejillones Peninsula beach-ridges, and Michilla; b) MT 2 of Isotope Stage 5 (about 125 ka B.P.) comprises the terraces of Antofagasta, Mejillones Peninsula beach-ridges, and Hornitos; c) MT 3 of Isotope Stage 7 (about 200 ka B.P.) contains the terraces of Antofagasta, Juan Lopez, Mejillones Peninsula beach-ridges, Hornitos, and El Rincon; d) MT 4 of Isotope Stage 9 (about 300 ka B.P.) is composed of the terraces at Antofagasta, La Portada, Juan Lopez, Hornitos, and La Rinada; e) MT 5 of Isotope Stage 11 consists of the terraces at Mejillones Peninsula beach-ridges and Hornitos.

4. The age dating methods for Pleistocene to Pliocene are done by ^{14}C, ESR, U-series, and aminoacid racemization. The composition of those methods provided

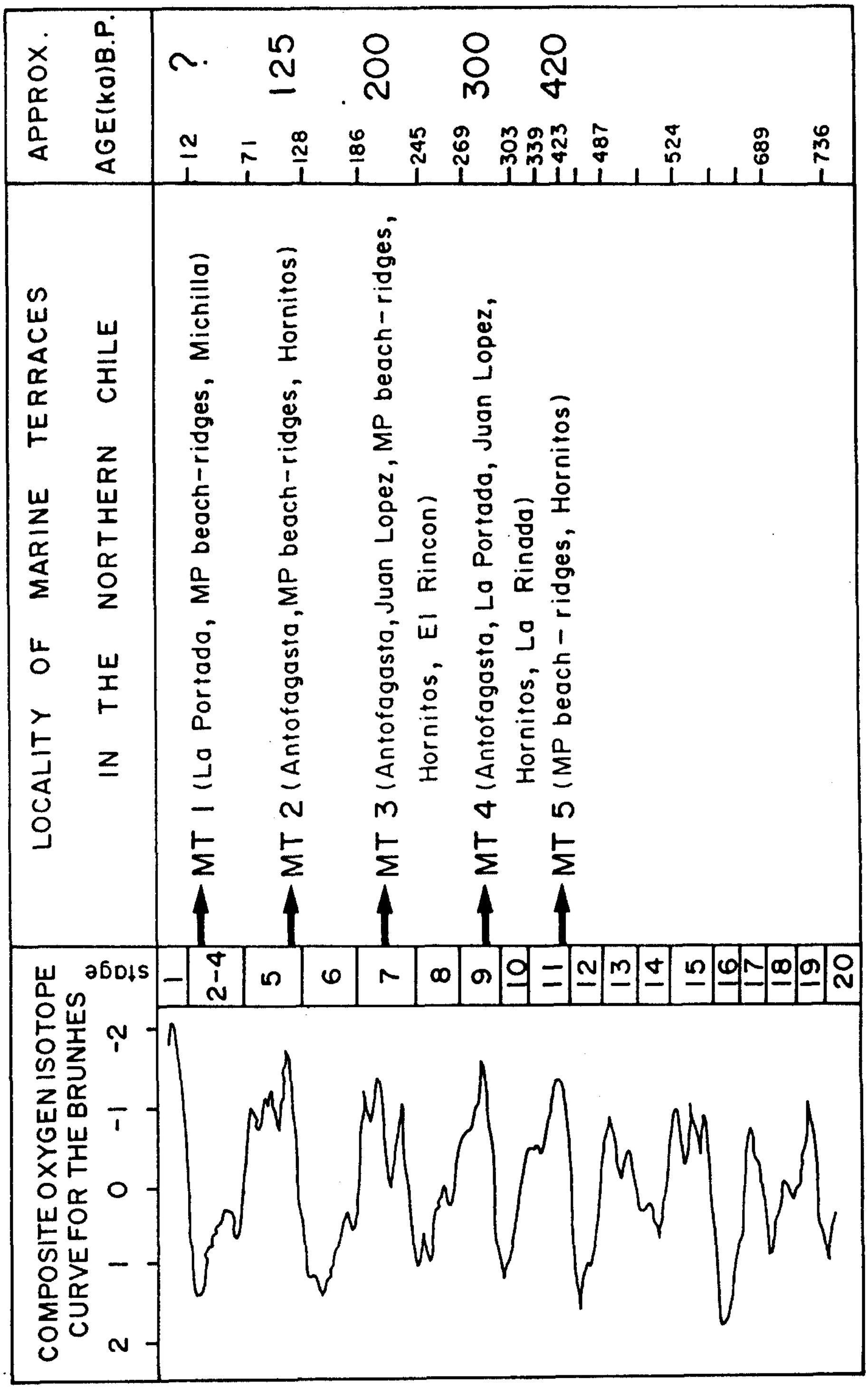

Fig. 14. Five distinguished MTs (Marine Terraces) in the northern coast of Chile. Oxygen Isotope curve on the left diagram is modified from Imbrie et al.,(1984) and Prell *et al.* (1986). The parentheses include the names of localities which are found each MT. For instance, MT 1 is found at La Portada, Mejillones Peninsula beach-ridges, and Michilla, etc.

high resolution of age datings within the same Isotope Stages and better correlations among the localities.

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