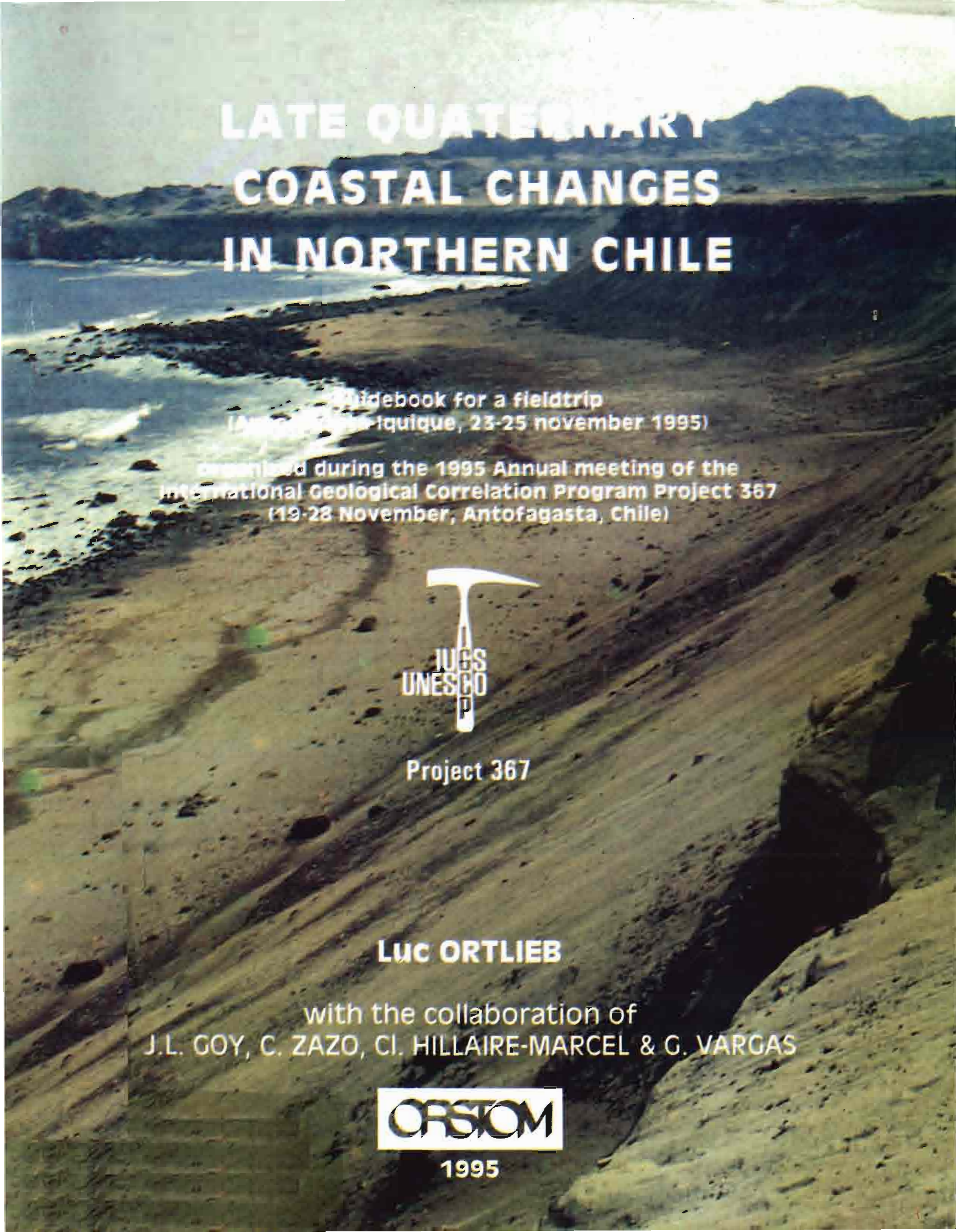

LATE QUATERNARY COASTAL CHANGES IN NORTHERN CHILE

Guidebook for a fieldtrip
(Antofagasta - Iquique, 23-25 november 1995)

Organized during the 1995 Annual meeting of the
International Geological Correlation Program Project 367
(19-28 November, Antofagasta, Chile)

IUGS
UNESCO

Project 367

Luc ORTLIEB

with the collaboration of
J.L. GOY, C. ZAZO, Cl. HILLAIRE-MARCEL & G. VARGAS

ORSTOM

1995

International Geological Correlation Program

1995 Annual meeting of IGCP Project 367

LATE QUATERNARY COASTAL RECORDS OF RAPID CHANGE: Application to present and future conditions

ANTOFAGASTA, Chile, 19-28 November 1995

Organizing Committee

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AUSPICES

International Geological Correlation Program-International Union of Geological Sciences
INQUA Commission on Quaternary Shorelines, INQUA Commission on Neotectonics,
CONICYT, ORSTOM (Dept. TOA, DIST), Instituto Chileno-Francés de Cultura
and the above mentioned universities.

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A BRIEF INTRODUCTION TO THE « NORTE GRANDE » OF CHILE

THE GEOMORPHOLOGICAL FRAMEWORK

The northern, arid, part of Chile is known as the « Norte Grande ». Geomorphologically this territory may be divided from west to east into 6 major units: a discontinuous, narrow, coastal plain, the Coastal Scarp, the Cordillera de la Costa, the intermediate depression (with Pampa del Tamarugal), the Precordillera (including mountain ranges of varying elevation, a wide pediplain and the prealtiplano depression), and finally the Andes Cordillera with the Altiplano (Fig. 0.0.1 & 0.0.2).

The coastal plain is only 1 or 2 km wide in long stretches of the area. Exceptionally, in the Peninsula of Mejillones, it reaches a larger width (15 km). The elevation of this coastal plain is generally less than 300 m. It was formed as a result of successive encroachments of the sea during Quaternary high seastand episodes. In a few places, and particularly in the Mejillones Peninsula, remnants of Pliocene transgressions can also be found. The coastal plain disappears completely north of Iquique (20°S).

The Coastal Scarp is a major geomorphological feature. It extends from Arica, at the boundary with Peru (18°S), to Taltal (25°30'S), with a mean height of 700 m. In its northern part, the Coastal Scarp is steeper and higher (ca. 1000 m) than in the Antofagasta region and more to the south.

The Coastal Cordillera is a continuous longitudinal mountain range, which runs parallel to the coastline. Its width varies between a few km to 50 km, and its peaks reach locally 2,000 m asl. In the Antofagasta-Tocopilla region, the Coastal Cordillera is mainly composed of thick Jurassic volcanic and volcano-sedimentary series (La Negra Formation).

The intermediate depression is formed by wide « pampas » (large plains formed by sediment infill within a mostly endorreic context). Pampa del Tamarugal extends about 200 km from north to south, and is some 40 km wide. These plains are located at a mean elevation of 1000 m asl.

The Precordillera is a complex geological unit with mountain ranges which can locally reach an elevation of 4000 m. East of the ranges, another depression was formed at the latitude of Antofagasta: it is occupied by the Salar de Atacama. This basin, partly filled-up with evaporitic sediments, lies at 2400 m and is about 85 km wide.

The Andes Cordillera is at its highest elevation in the north of Chile. The highest peaks are formed by recent volcanic cones. Immediately to the east of the water divide, at a 4000 m elevation, extends the flat feature called Chilean Altiplano (which does not precisely correspond to the Altiplano of Bolivia or southern Peru).

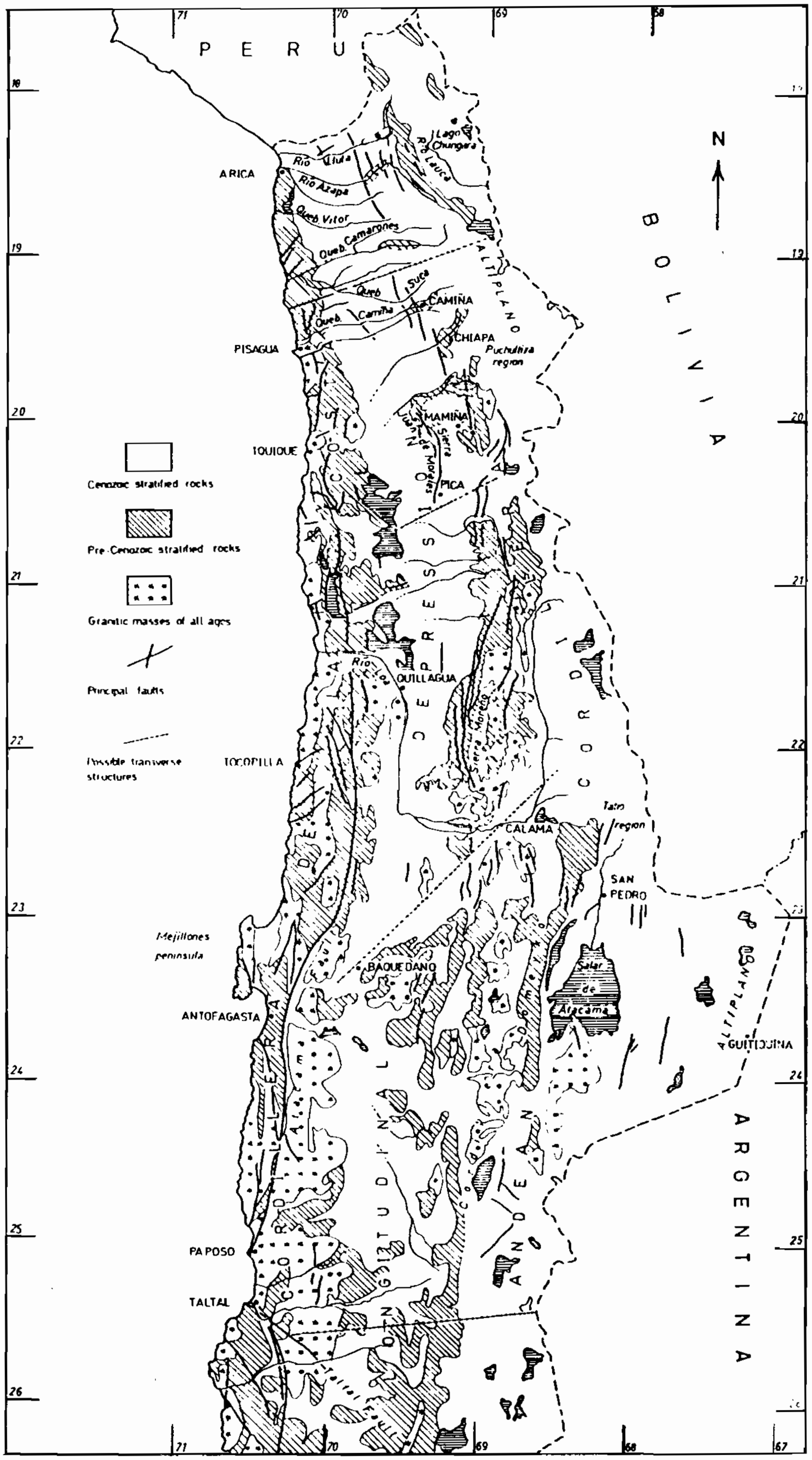


Fig. 0.0.1.- Simplified geological map and major fractures of northern Chile (from Mortimer & Saric, 1975).

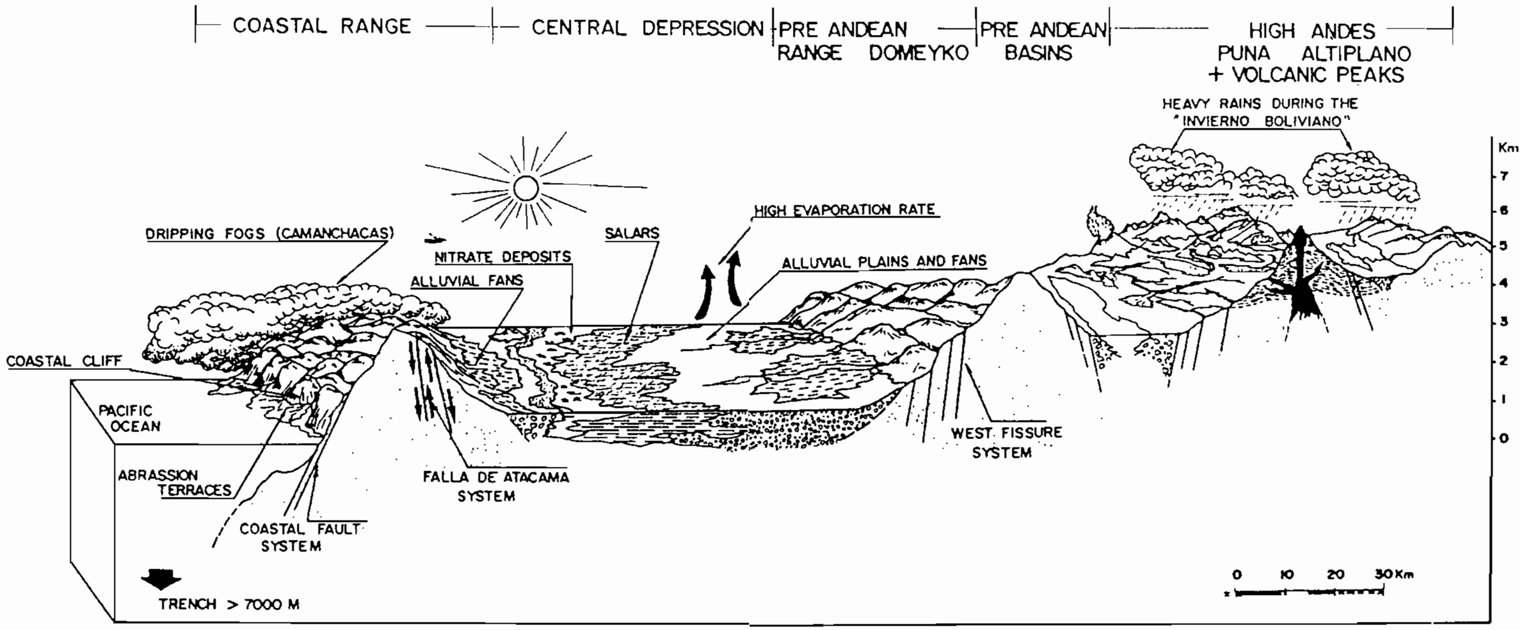


Fig. 0.0.2.- Schematic sketch of the major geomorphological units of the « Norte Grande » of Chile (from Chong, 1988).

CLIMATE

Without doubt the outstanding particularity of the « Norte Grande » is the extreme aridity of its climate. The Atacama Desert is generally considered as the most arid place on earth. Large areas of the Pampa de Tamarugal and surrounding areas do not receive any precipitation in decades. And when some rain falls, it is in minor quantity (on normal standards, that is a few centimetre at most), and in localised areas only.

Within the coastal desert of Peru and Chile, the northern Chile sector is the most arid one (Fig. 0.0.3), the sector where even the cactus or Tillandsias cannot survive. Most of the area covered by the Norte Grande (except the Andes Cordillera) receives less precipitation than 10 mm per year (value calculated on an interannual basis, of course) (Fig. 0.0.4).

The precipitation pattern of the cordilleran region is distinct from the rest of the Norte Grande because this area receives, in summer, some rainfall from the amazonian domain. The relatively regular rainy period in the Andean region is called the « invierno boliviano », or « invierno altiplánico », because the Spaniard conquistadores used to refer to the rainy season as « winter ».

The extreme aridity of the Norte Grande is classically attributed to a conjunction of atmospheric, oceanographic and orographic factors. The 4,000-5,000 m high Andes Cordillera prevents the humid air of the Atlantic and Amazonian region from reaching the North of Chile. For a series of reasons the Pacific Ocean does not provide water vapour which might fall as precipitation. The cool Humboldt Current and the associated upwelling phenomena strongly limit the evaporation of sea water. The almost permanent southeastern Pacific anticyclonic cell also produces conditions which reinforce the general lack of rainfall (thermal inversion, atmospheric subsidence, upwelling, Trade winds). The Fig. 0.0.5 depicts some of these oceanographic and atmospheric regional features.

In an area which owes its climate to strong ocean-atmosphere interactions, it is no surprise that the El Niño oceano-climatic anomaly also plays a role in the regional climate. Nevertheless, the regime of anomalous precipitation is less directly controlled by the ENSO system than the coast of northern Peru and the area of Central Chile (Rutllant, 1977, 1978, Rutllant & Fuenzalida, 1991). In Antofagasta, for instance, no clear correlation could be established between El Niño and the strongest rainfalls (Fig.0.0.6).

Vegetation and fauna

The vegetation of the Norte Grande is limited to xerophytic plants. Along the coast, and particularly at an altitude of over +500 m on the edge of the Cordillera de la Costa. cactus are found, generally in scarce numbers. In the pampa of the intermdiate depression, the most common trees are the « tamarugo » (*Prosopis tamarugo*), the chañar (*Guffroea decorticans*) and the algarrobo (*Prosopis chilensis*).

The general lack of vegetation in the Atacama Desert makes it one of the regions of the world with the least number of species of terrestrial fauna.

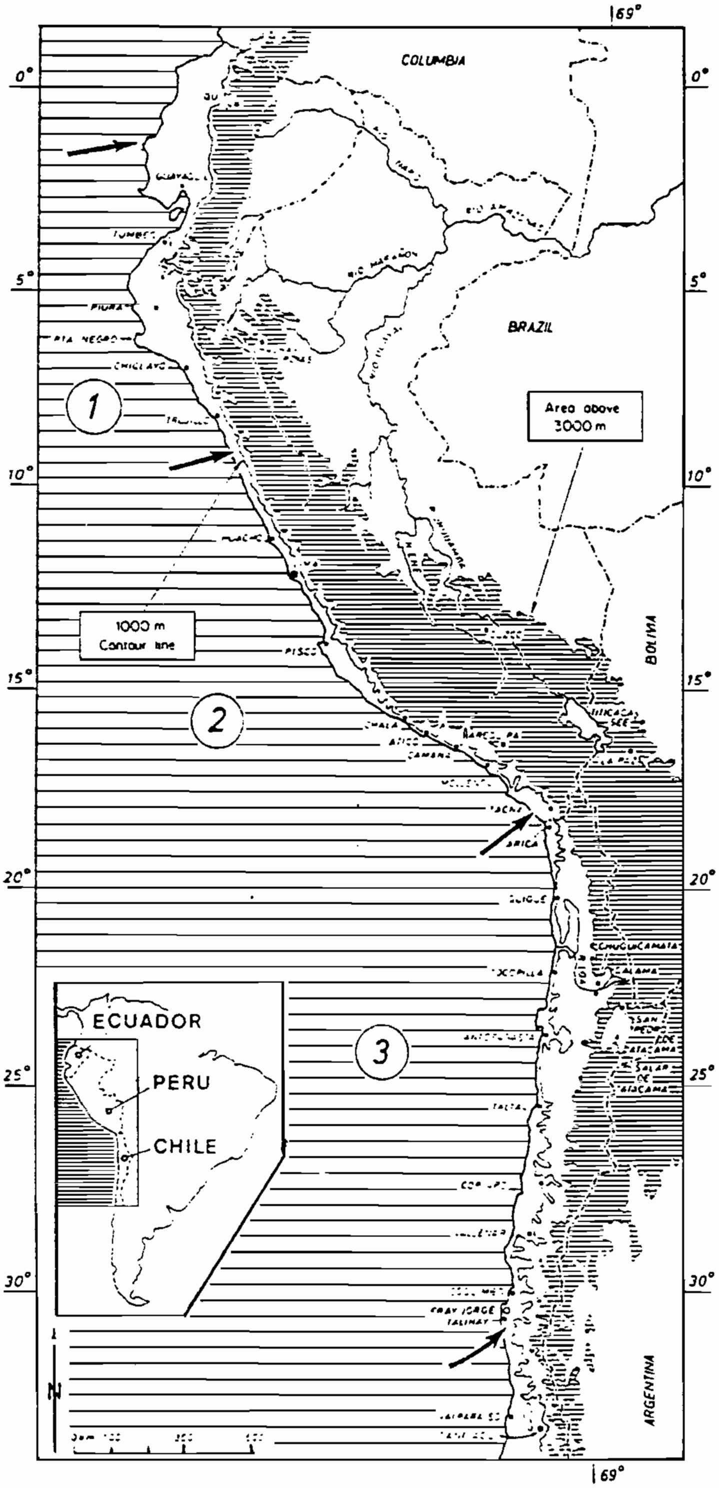


Fig. 0.0.3.- The coastal desert of southwestern South America can be divided into three sectors, the Chilean sector, with the Atacama Desert, being the most arid one (from Rauh, 1985).

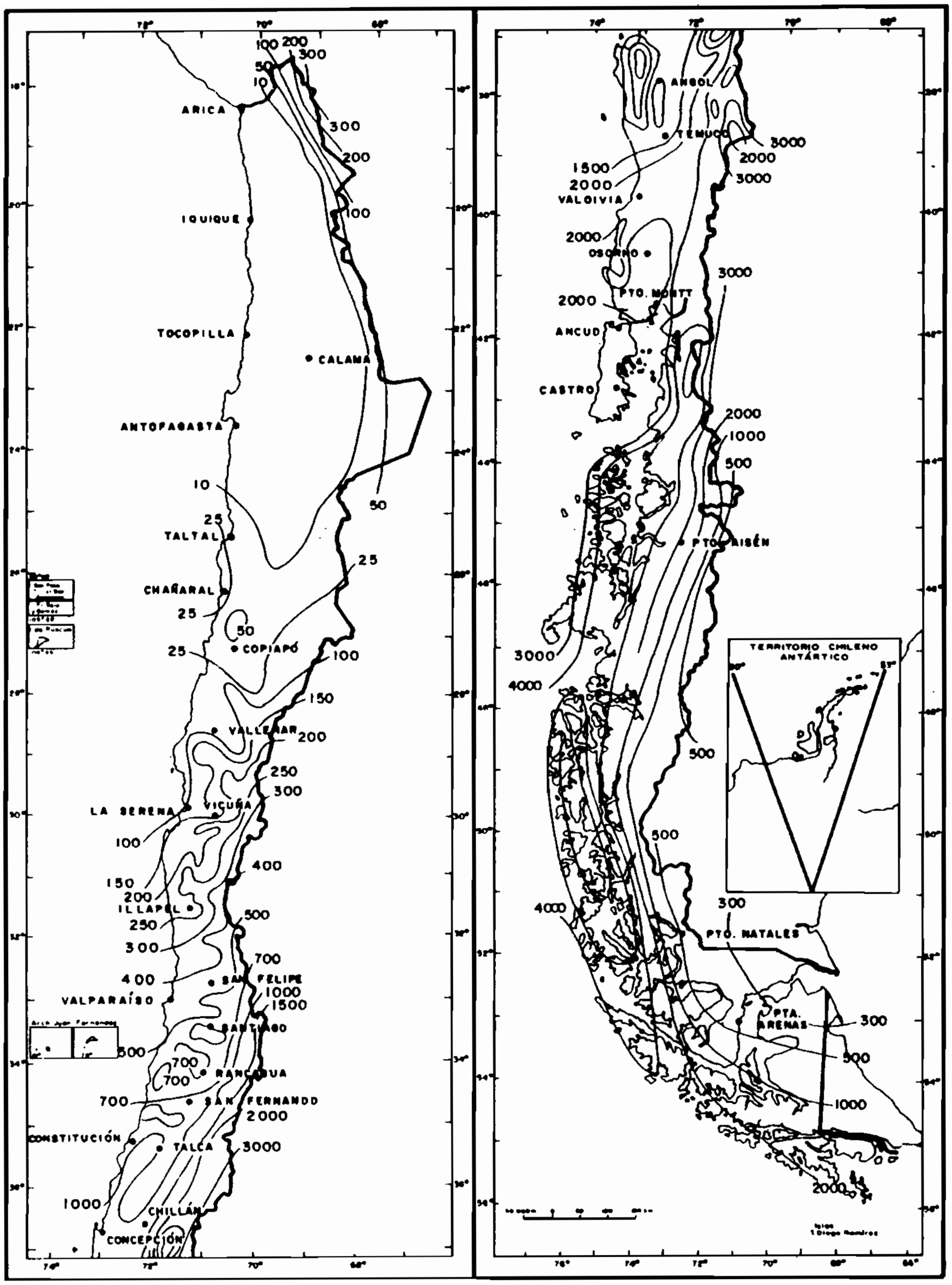


Fig. 0.0.4.- Mean annual precipitation in Chile (from Huber, 1979).

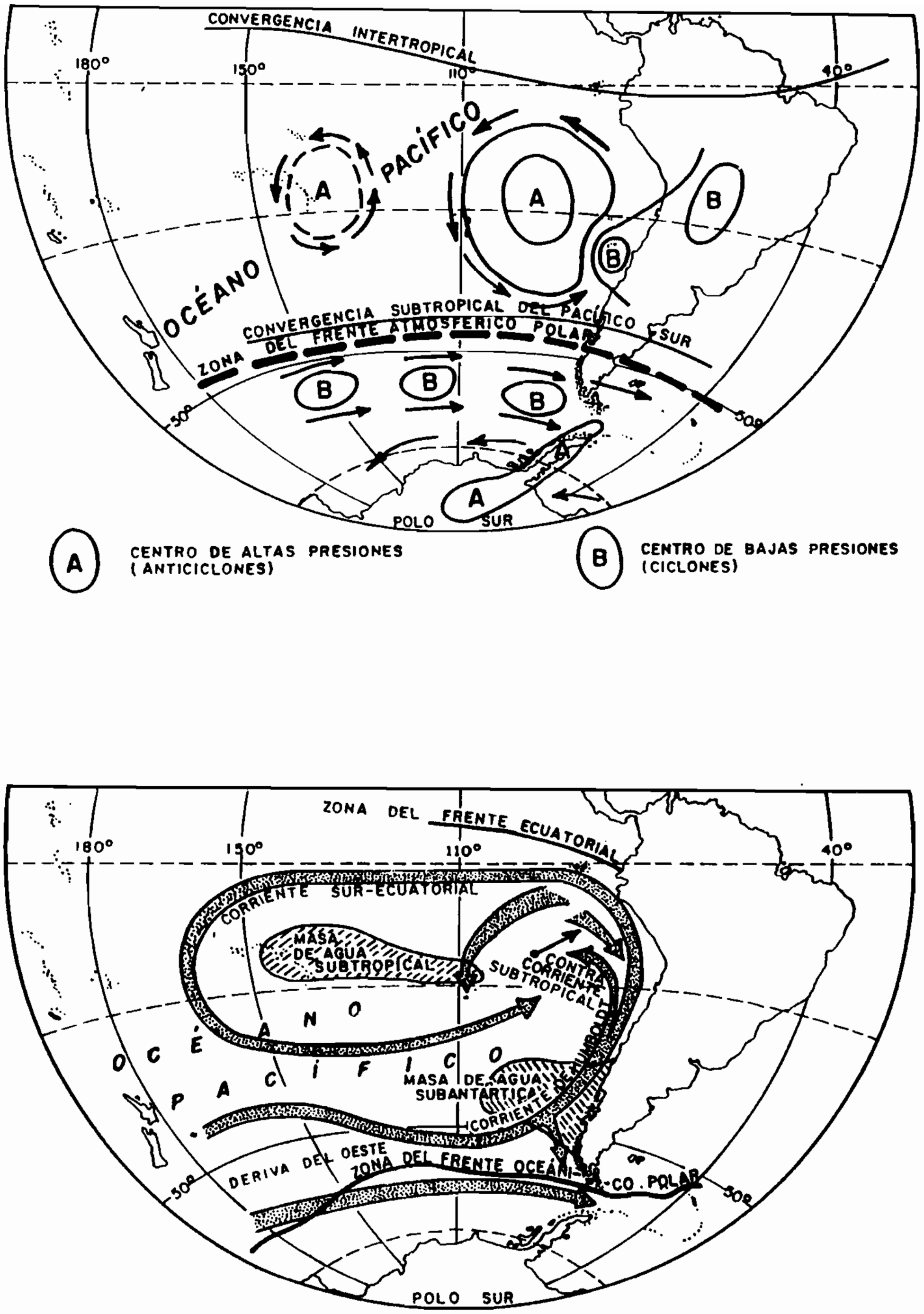


Fig. 0.05.- Oceanic and atmospheric general circulation systems in the southeastern Pacific region (from Romero, 1985).

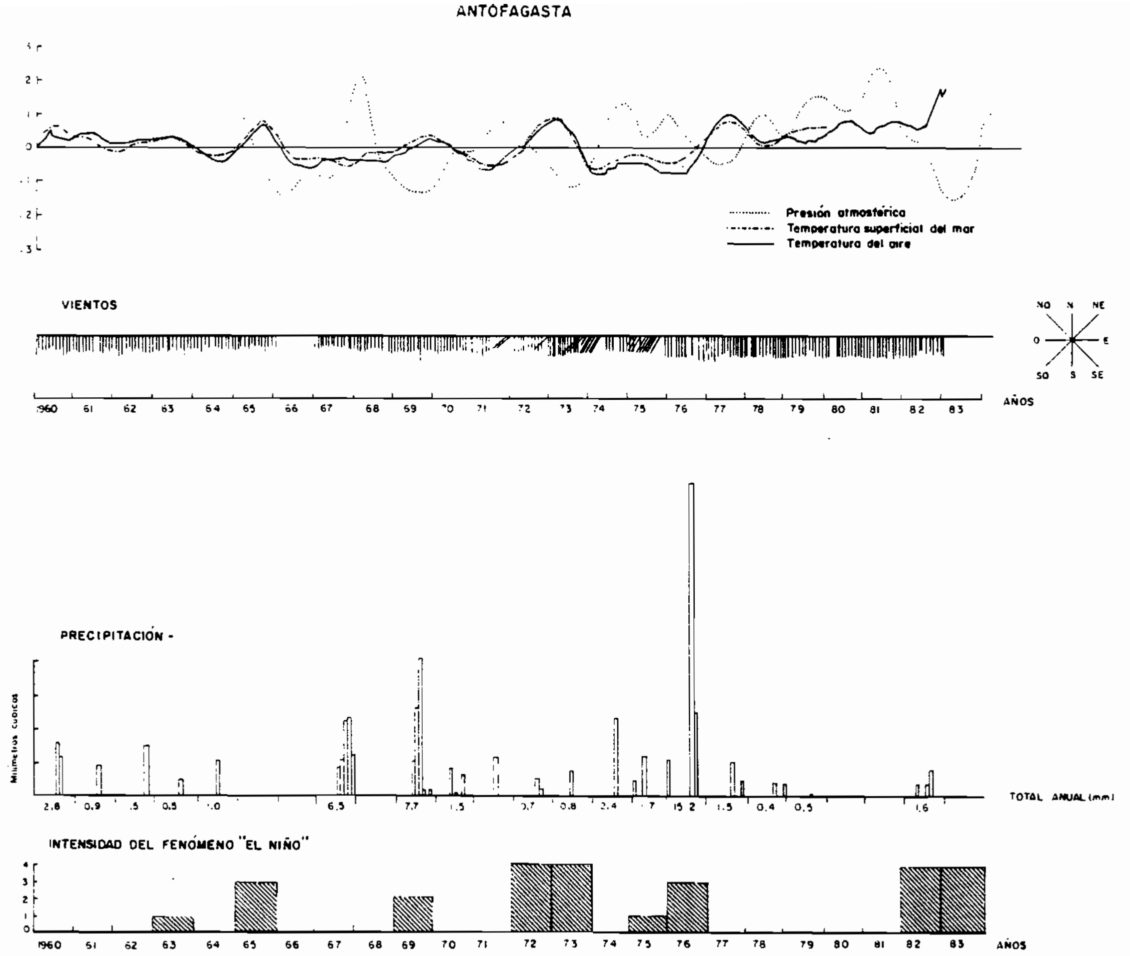


Fig. 0.0.6.- Some oceanic and meteorological data at Antofagasta between 1960 and 1983 (from top to bottom): mean monthly SST (°C), atmospheric pressure (mb), air temperature (°C), wind direction and intensity (n/h), and annual precipitation (from Romero, 1985).

THE PLATE BOUNDARY

The tectonic and structural framework of the Norte Grande of Chile is dominated by the plate boundary feature. The geometry of the subduction of the Nazca plate under the South America plate was precisely determined through seismological studies (Fig. 0.0.7, 0.0.8, 0.0.9). The relatively steep dip angle of the slab has major consequences on the Andes structural evolution.

The northern Chile-Southern Peru seismic gap was slightly reduced in July 1995 after the occurrence of the Antofagasta earthquake (Ms 7.3)(Fig. 0.010).

The deepest sector of the Chile Peru Trench is located near Antofagasta (8,000 m) (Fig. 0.0.11). According to some sources (AAPG, 1981), an unnamed aseismic ridge, grossly parallel to the Nazca Ridge, is found offshore Antofagasta (Fig. 0.0.12). Antofagasta is also located in the area where the Central Andes major domains are at their widest development.

The tectonic and structural regional setting accounts for the late Quaternary deformations in the area of Antofagasta and Mejillones Peninsula. During the fieldtrip (Fig. 0.0.13), we shall examine some of the effects of these deformations, at distinct time scales.

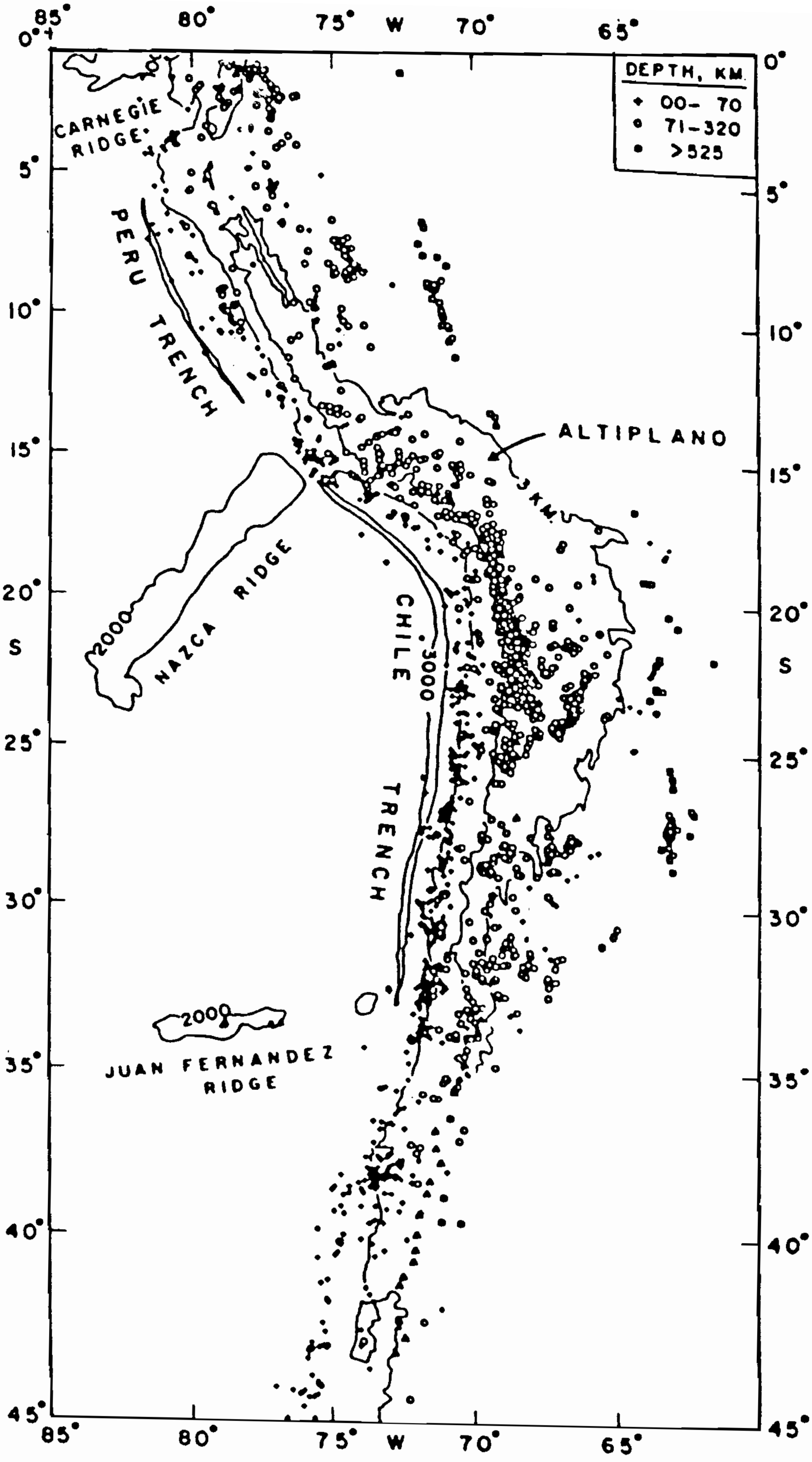


Fig. 0.0.7.- Distribution of seismicity in southwestern South America (from Baranzagi & Isacks, 1976).

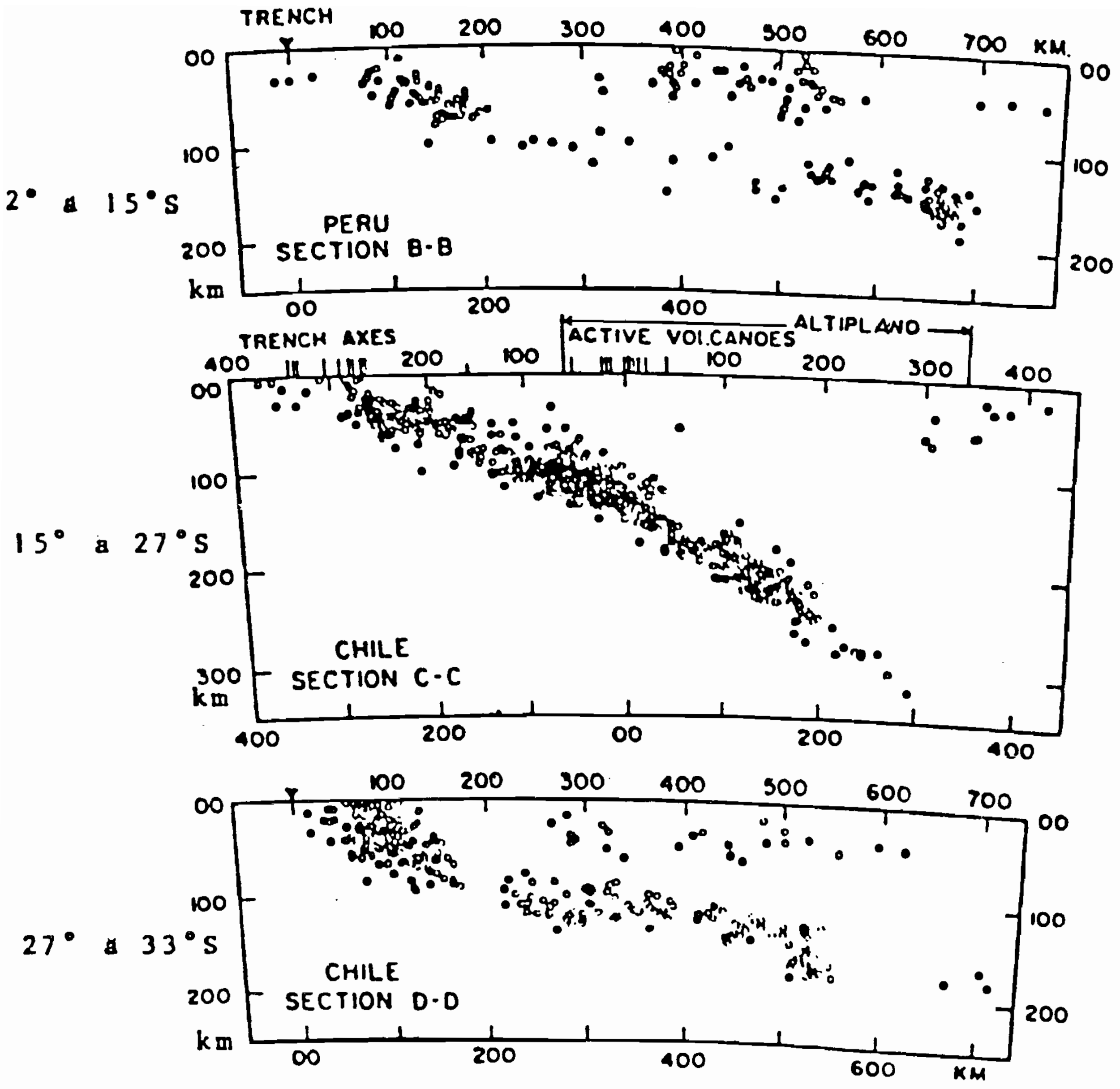


Fig. 0.0.8.- Geometrical disposition of the Nazca plate along the western coast of South America, at the latitude of northern Peru, northern Chile and southern Chile (from Barazangi & Isacks, 1976).

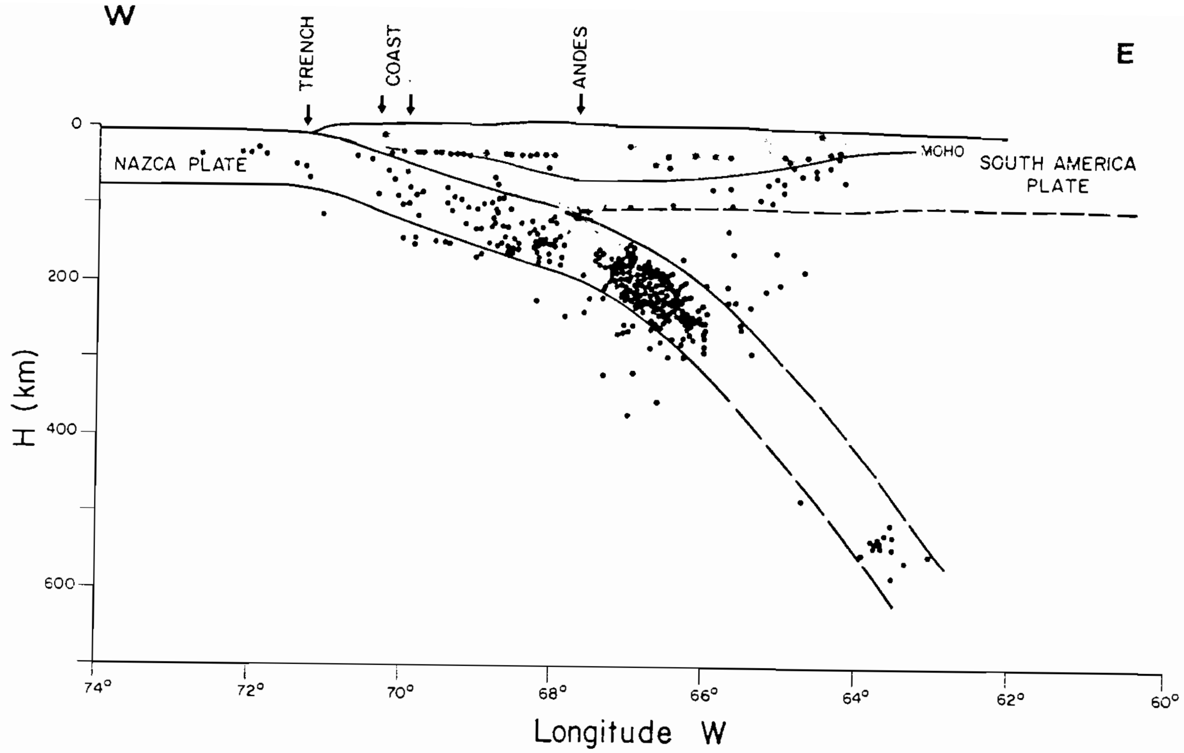


Fig. 0.0.9 .- Subduction of the Nazca plate under South America, at the latitude of Antofagasta (23°S), with indication of the general sismicity of the area (from Kausel & Campos, 1992).

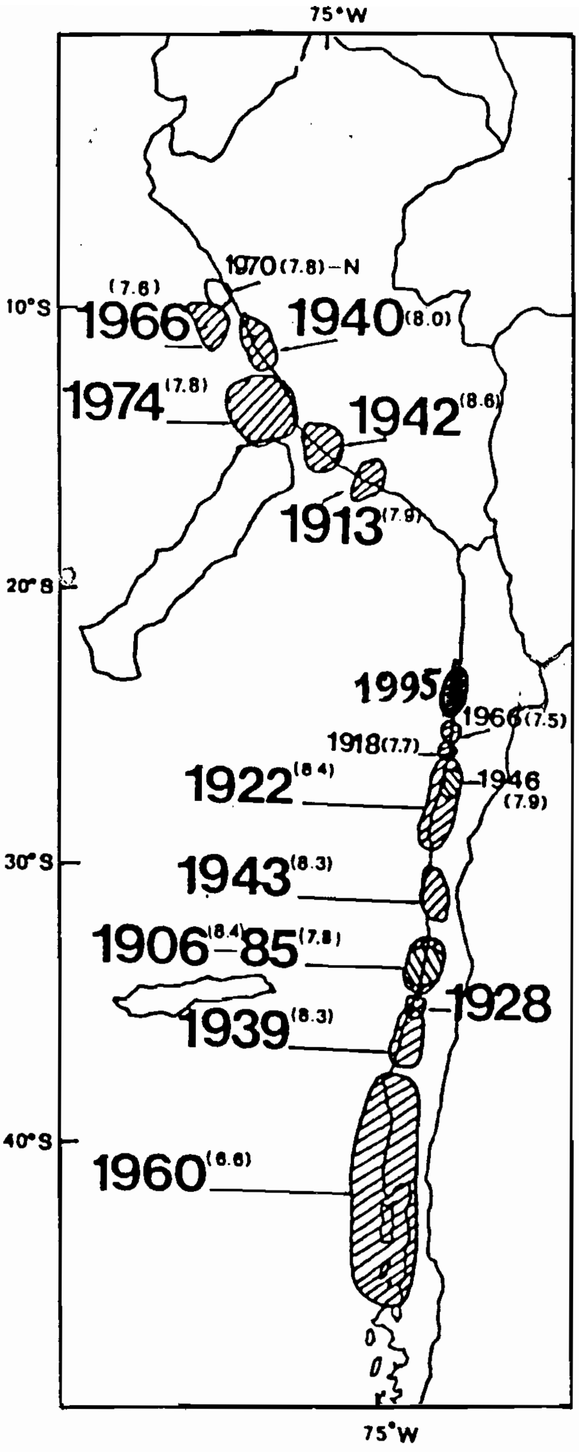


Fig. 0.0.10.- XXth century earthquakes of magnitude greater than 8 along the Peru-Chile coast, with indication of the approximate surface of fault rupture (modified from Campos, unpubl.).

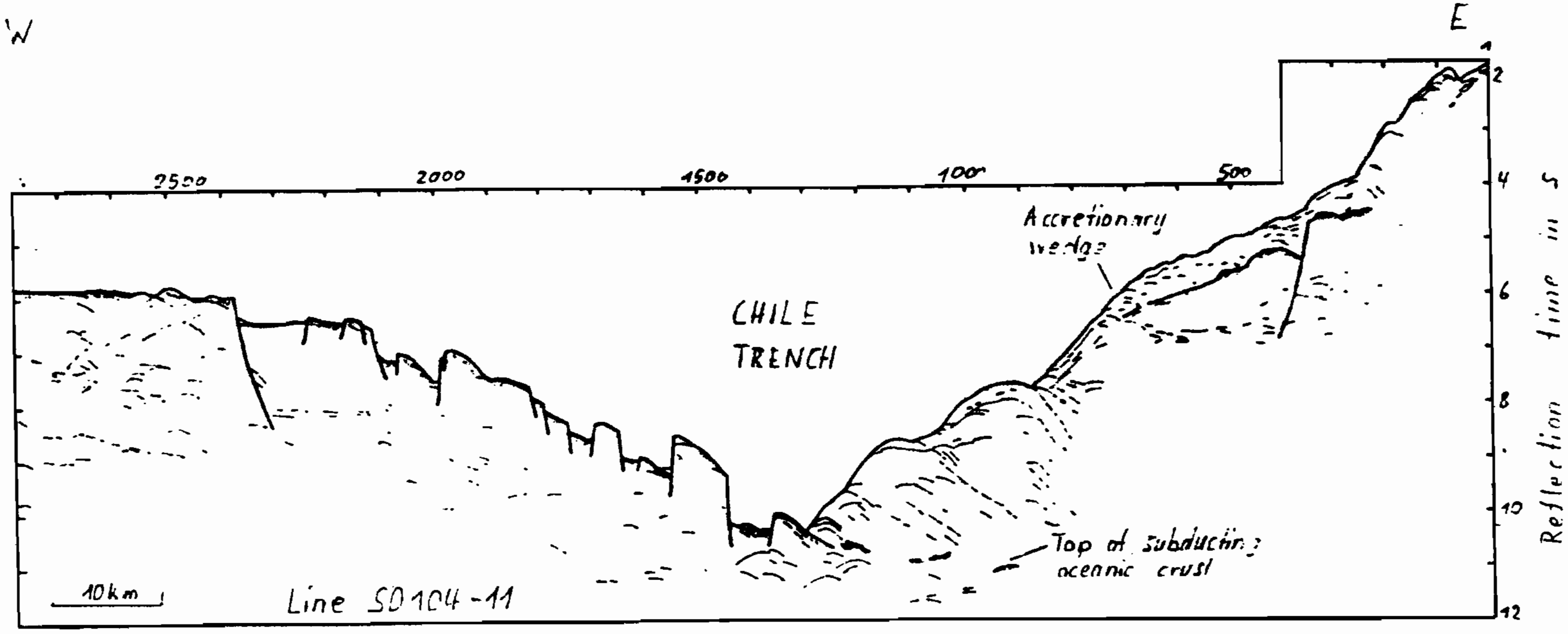


Fig. 0.0.11.- Seismic profile offshore Michilla (NW of Antofagasta) recently obtained by the CINCA Project (unpublished data).

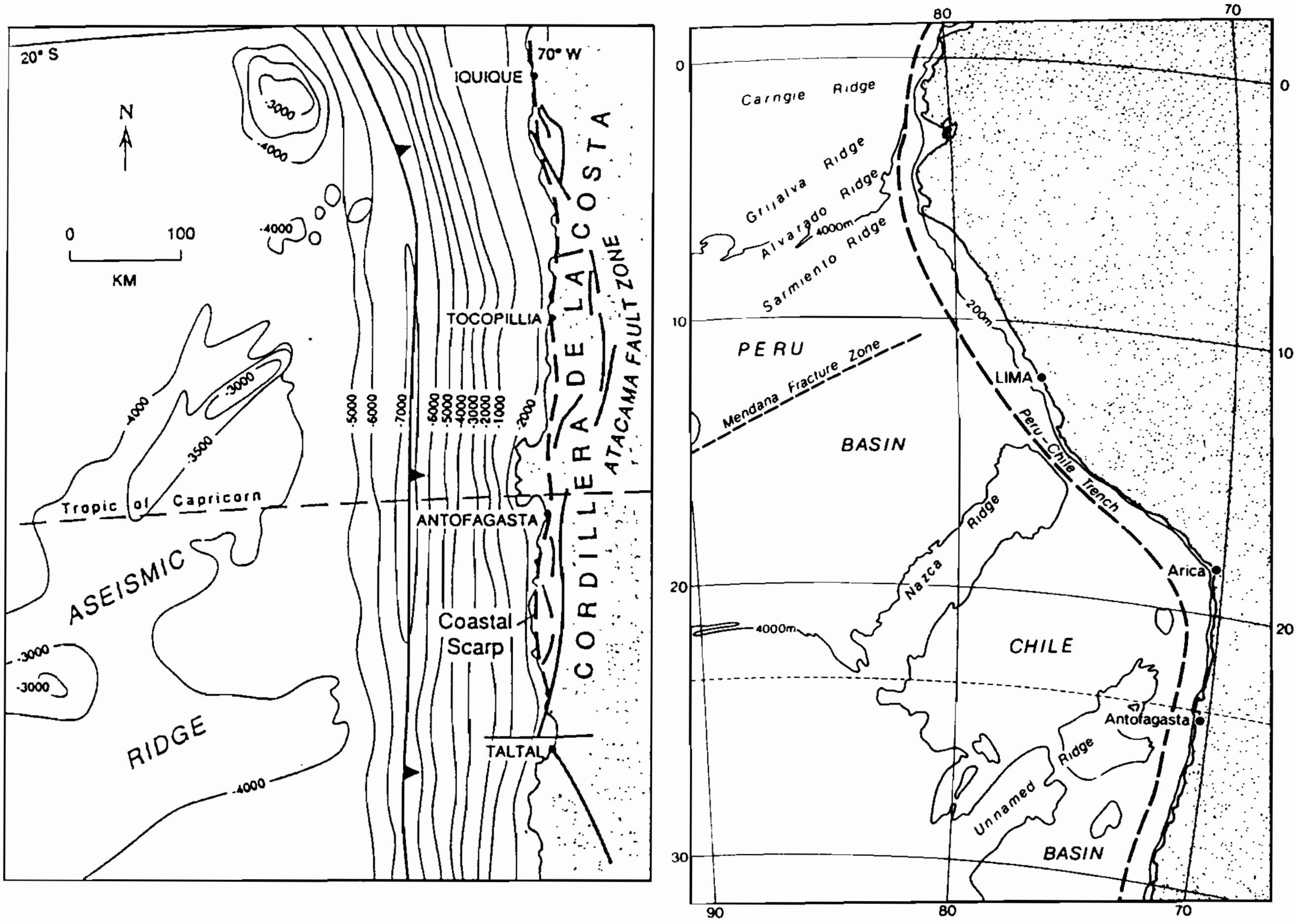


Fig. 0.0.12.- Maps of the SE Pacific Ocean floor showing the possible existence of an unnamed aseismic ridge in front of the Antofagasta (from Flint et al., 1991, right, and Hartley & Jolley, 1995, left). It has been hypothesised that such a subducting aseismic ridge might be related with the geometry of the Atacama Fault system.

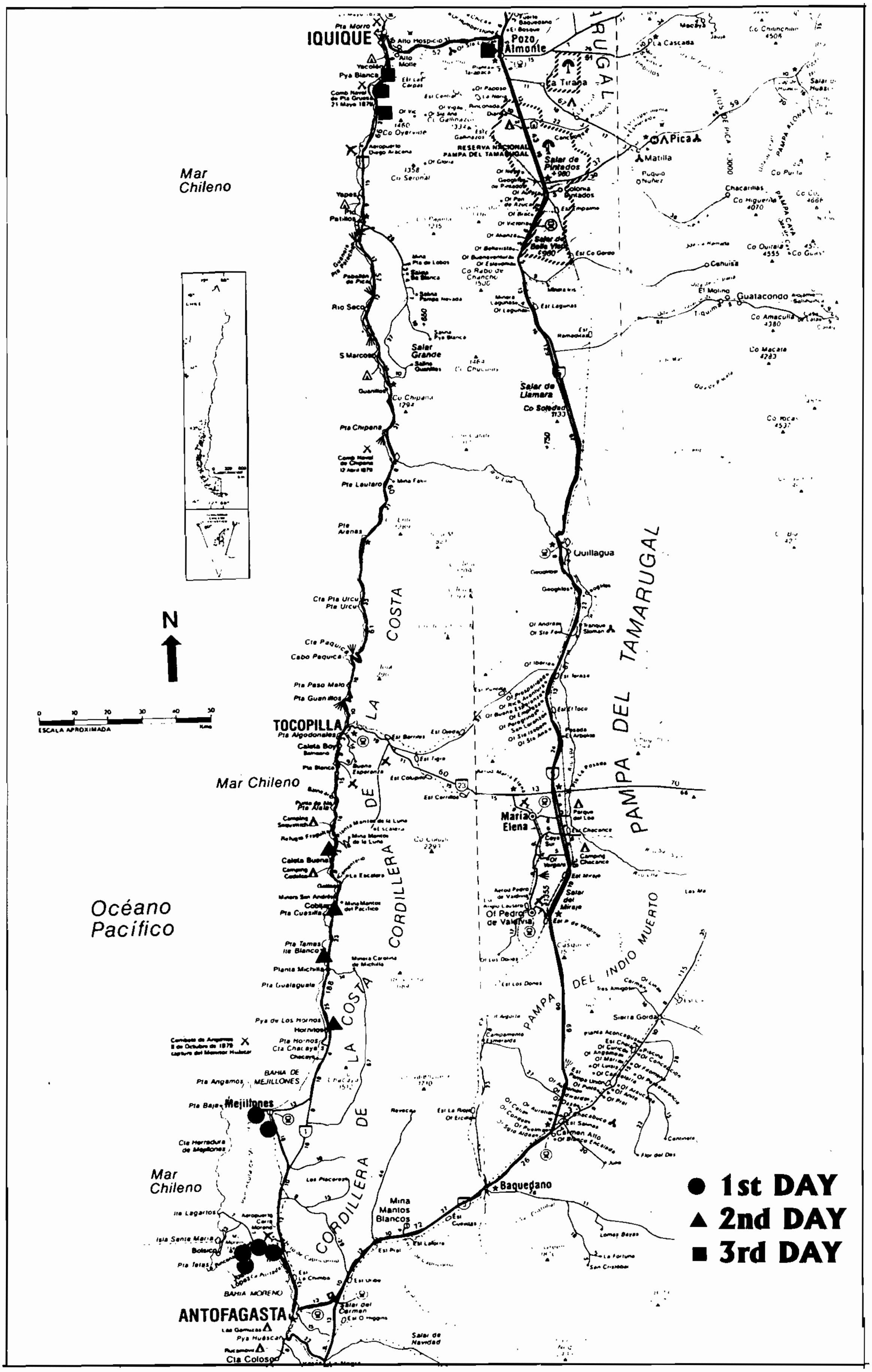


Fig. 0.0.13.- General location map of the stops during the three days of the main fieldtrip organised for the II annual meeting of IGCP Project 367, in november 1995.

LATE QUATERNARY COASTAL CHANGES IN NORTHERN CHILE

Guidebook for a fieldtrip
(Antofagasta-Iquique, 23-25 november 1995)

organized during the 1995 Annual meeting of the
International Geological Correlation Program Project 367
(19-28 November, Antofagasta, Chile)

Short excursion around Antofagasta (22.11.1995)

COLOSO: MARINE TERRACES AND LATE QUATERNARY ALLUVIAL SEDIMENTATION

The first stop of the preliminary excursion will lead the participants to Caleta Coloso, in the southernmost part of the bay of Antofagasta (Fig.0.1.1). There, we shall examine three major wave cut terraces and an alluvial sequence that could be correlated with the Late Quaternary.

Beside, we shall discuss the chronostratigraphic interpretation of the highest marine terrace in this part of Antofagasta bay.

The Pleistocene marine terraces

Caleta Coloso presents three marine terraces (Fig. 0.1.2). The oldest and most elevated one is also the most conspicuous, even from the distance (Fig. 0.1.3). It lies at +70 m asl., and was attributed to a Pliocene transgression (Martinez & Niemeyer, 1982).

The intermediate terrace is found at +30 m at the mouth of Quebrada Jorgillo (Fig. 0.1.3.). Electron Spin Resonance (ESR) and Uranium /Thorium analyses performed by Radtke (1989) on mollusk shells of the second terrace yielded uncertain results (Fig. 0.1.4).

The youngest marine terrace is preserved at the mouth of the same Quebrada Jorgillo, at an elevation of +6 m (Fig. 0.1.5). ESR and U-series dating on material of the marine deposit associated to the lowest terrace point to a last interglacial age (Fig. 0.1.4). A concordant interpretation was reached through a new set of U-series dating and amino-acid racemisation method (Ortlieb et al., 1993). This marine deposit, which had been interpreted some time ago as « Cachaguian » (a 30-ka stage) by Paskoff (1973), is now assigned to the last interglacial highest sea-level stand (isotopic substage 5e, 125 ka).

Late Quaternary alluvial sequence

At the mouth of Quebrada Jorgillo, a sequence of up to 10 m of alluvial sediments are preserved above the marine sediments associated to the last interglacial, or above the wave-cut abrasion surface of the same high seastand episode. This geometric disposition provides a useful chronological control on the alluvial sequence. The sequence is part of a system of alluvial fans and smaller cones, built at the foot of the coastal escarpment. Three units may be distinguished in this sequence, on the basis of textural and sedimentary criteria.

During the Holocene, the floods of Quebrada Jorgillo dissected the alluvial sequence preserved along the Coloso embayment. North of the quebrada mouth, the sediments are mudflows and debris-flow deposits which inherit the reddish colour from the Caleta Coloso Fm. South of the axis of the quebrada, the alluvial sequence consists in intertonguing « fluvial » units and debris-flow deposits of a distinct (tan) colour related to the metamorphic and intrusive grey substrate (Bolfin Fm, see Fig. 0.1.1). The sediments of the « fluvial » unit come from a large watershed within the Cordillera de la Costa (ca. 40 km^2), while the debrisflow sediments were carried on much shorter distances from smaller watersheds.

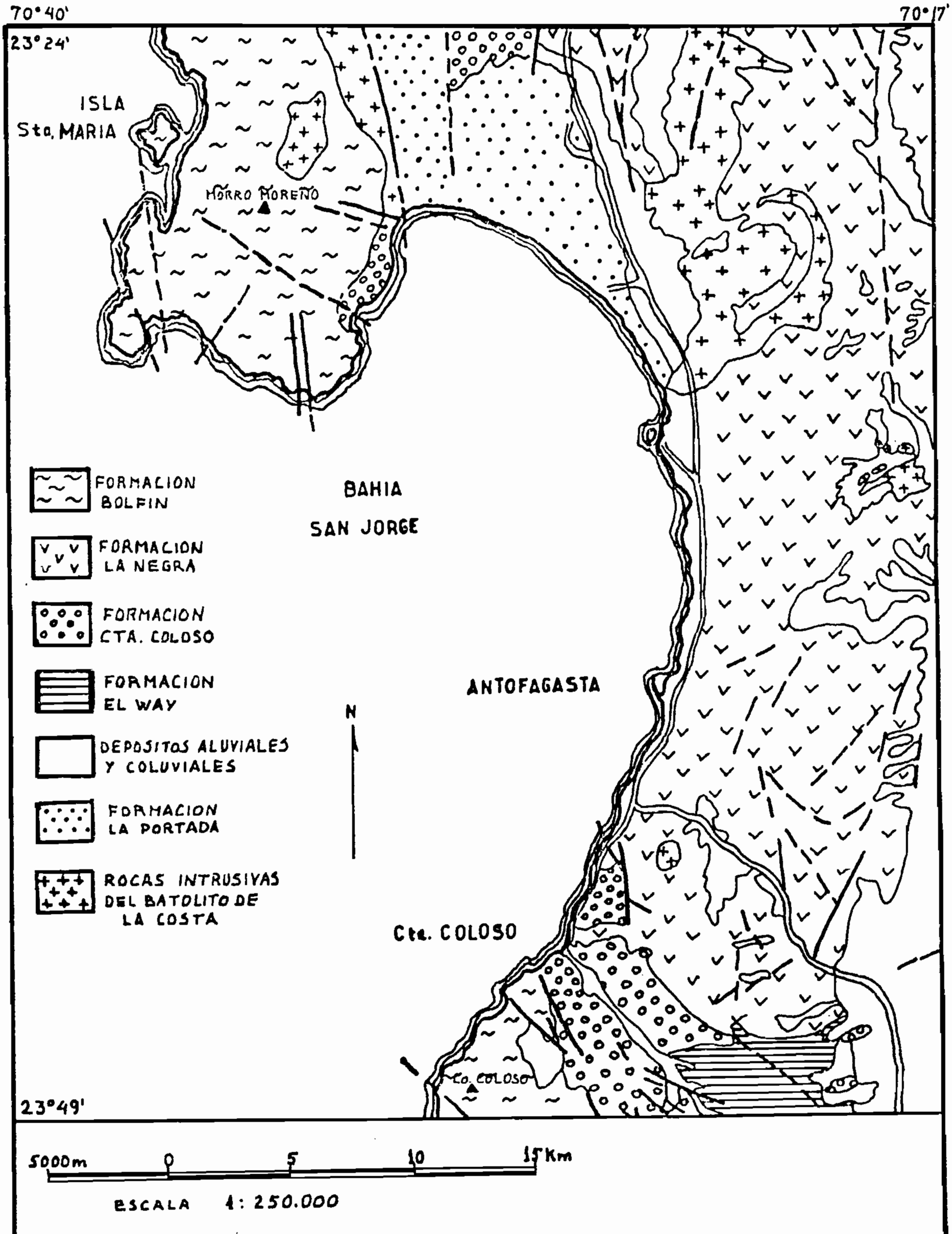


FIG. 2 MAPA GEOLOGICO SIMPLIFICADO

Fig. 0.1.1.- Geological sketch map of Antofagasta bay (from Alonso et al., 1982). At Caleta Coloso where will be the first stop, we whall see the Cretaceous Caleta Coloso Fm, and the intrusives of the Bolfín Fm.

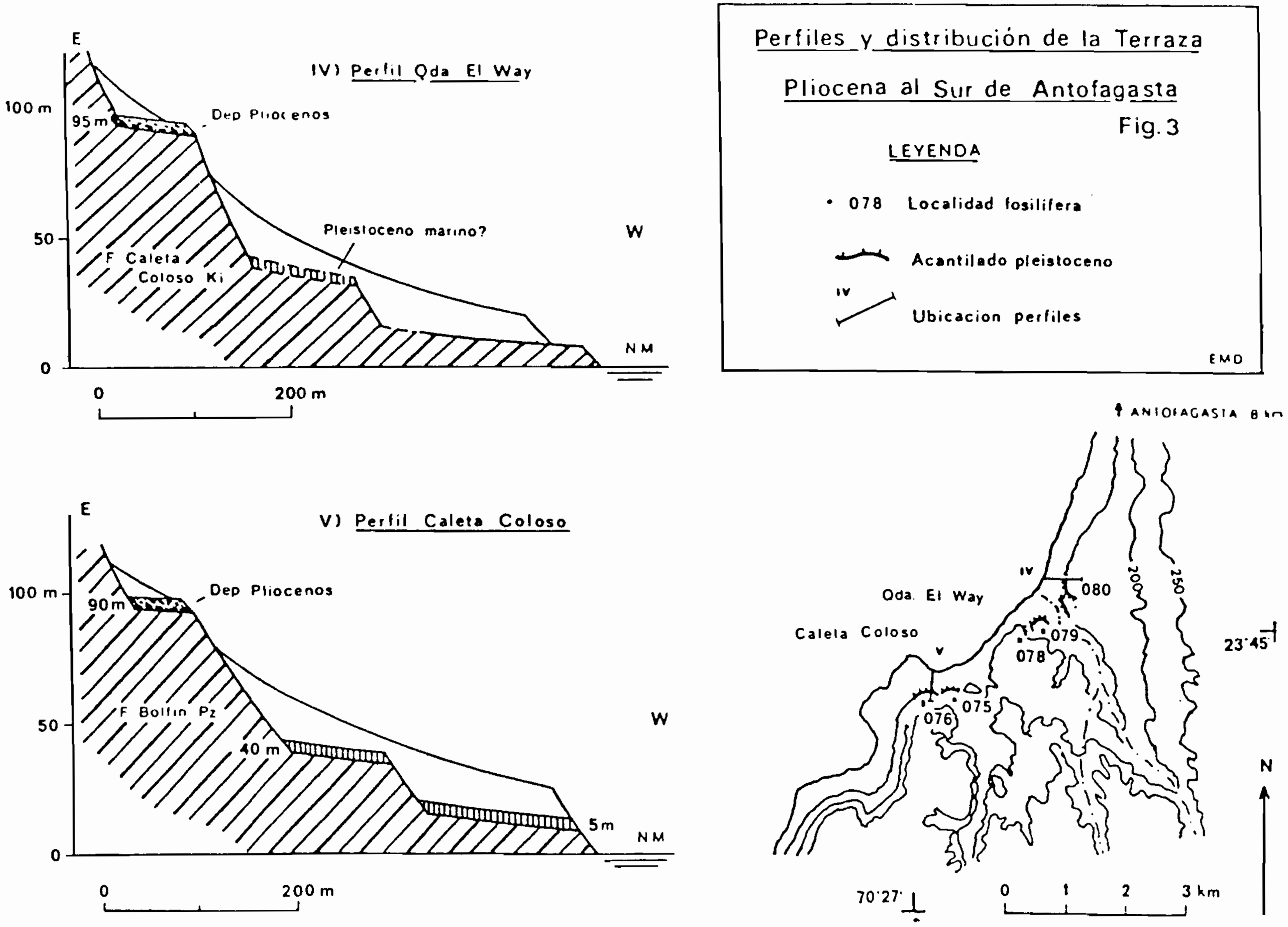


Fig. 0.1.2.- The three marine terraces at Caleta Coloso (from Martinez & Niemeyer, 1982). The authors interpreted that the highest terrace was formed during the Pliocene, but we observed a Pleistocene fauna in the thin deposits covering the abrasion platform.

Fig. 0.1.3.- View of Cerro Coloso, from Antofagasta (i.e. toward the South). The large notch formed at the base of the mountain slope (at ca. + 100 m asl), should represent the highest level reached by the sea since Pliocene times.

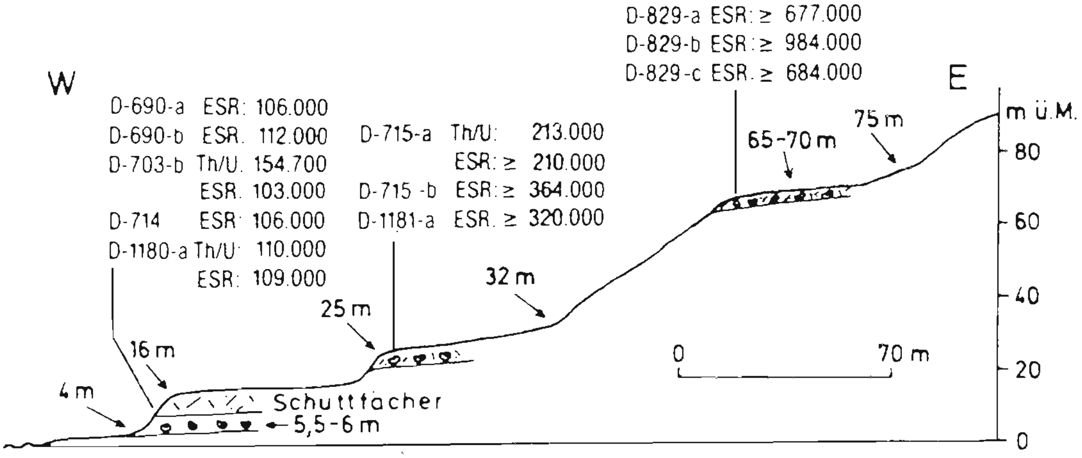


Fig. 0.1.4.- Geochronological results (Electron Spin Resonance and U-series) obtained by Radtke (1989) on mollusk shells from the three terraces.

Fig. 0.1.5.- The Late Quaternary sequence at Caleta Coloso, showing the last interglacial marine deposit (to the right of vehicle) unconformably covered by several metres of alluvial sediments. Maximum elevation of the marine sediments is ca. +6 m asl.

In the northern cliff, three sub-units were identified: the younger one consists in relatively thick beds with a chaotic texture; while the middle one includes more numerous graded-bedding structures and imbricated clasts (which involve more water in the sedimentary process). The relatively thin upper sub-unit compares texturally with the lowest part of the sequence. The differences observed throughout the alluvial sequence are interpreted as the result of climatic variations in the last glacial/interglacial cycle: they may depict a succession of arid, then semi-arid, and finally, arid conditions.

The « Pliocene » age of the Antofagasta terrace

The conspicuous marine terrace located at a ca. +100 m elevation at Antofagasta was assigned a Pliocene age by Martinez & Niemeyer (1982). This feature was unformally named « Antofagasta Terrace » by the above mentioned authors. The relatively flat, slightly seawards dipping, erosional surface (on which were built the Antofagasta cemetery and the Coviefi residential quarter) is several hundred metres wide (Fig. 0.1.7). It is well preserved between the quebradas Salar del Carmen and La Negra, but isolated remnants of the same feature are found also more to the south at Jardines del Sur residential quarter and at Punta Coloso (Fig. 0.1.2 & 0.1.4).

At Antofagasta, the terrace is better preserved in the interfluves between the major quebrada outlets. At its inner edge, it is covered by alluvial fan deposits and slope debris of Quaternary age (Vargas, in prep.). The elevation of the marine terrace decreases slightly from north to south, from about +110 m at the north of the town to less than +80 m at Punta Coloso (a 10-km long coastal sector) (Fig. 1.0.7).

Paleontological age of the terrace

The marine platform was cut in La Negra Fm. lavas of Jurassic age. A thin veneer of fossiliferous nearshore sediments were found in a few localities. Most of the fossiliferous localities indicated by Martinez & Niemeyer (1982) within the city are not accessible anymore (buildings are now covering most of the terrace). These authors did not present the faunal content of each localities, and only provided a global list for the Antofagasta Terrace. In this list are included typical Pliocene elements like: *Chlamys vidali, Fissurella concolor, Concholepas nodosa, Fusinus remondi, Nucella mirabilis,* and other species which are still extant: *Glycymeris ovata, Chroromytilus chorus, Chama pellucida, Venus (=Protothaca) antiqua, Tegula atra, Nucella crassilabrum crassilabrum, Oliva peruviana* and *Balanus psittacus*. The faunal composition of the marine sediments overlying the wave-cut platform led the authors to assign a Pliocene age to the geomorphic feature. Thus the terrace would be penecontemporaneous with the La Portada Fm. as defined by Ferraris & Di Biase (1978).

More recent studies and sampling of fossiliferous sediments overlying the marine platform were performed at a few localities of the Antofagasta Terrace (Ortlieb, unpublished).

At one locality, not mentioned by Martinez & Niemeyer (1982), in the SE part of the Coviefi quarter, at the outlet of the quebrada La Negra, a thin coquina deposit with diagnostic Pliocene species of mollusks (*Chlamys vidali* and/or *Chlamys hupeanus*, and *Concholepas* cf *C. nodosa*) was observed. The unit has a sedimentary facies quite similar to that of the La Portada Fm, at La Portada locality (Stop 1-1). At the +90 m Coviefi locality, the Pliocene unit is unconformably lying above mesozoic volcanic substrate, or upon older colluvial sediments which include lenses of volcanic ashes. A geochronological

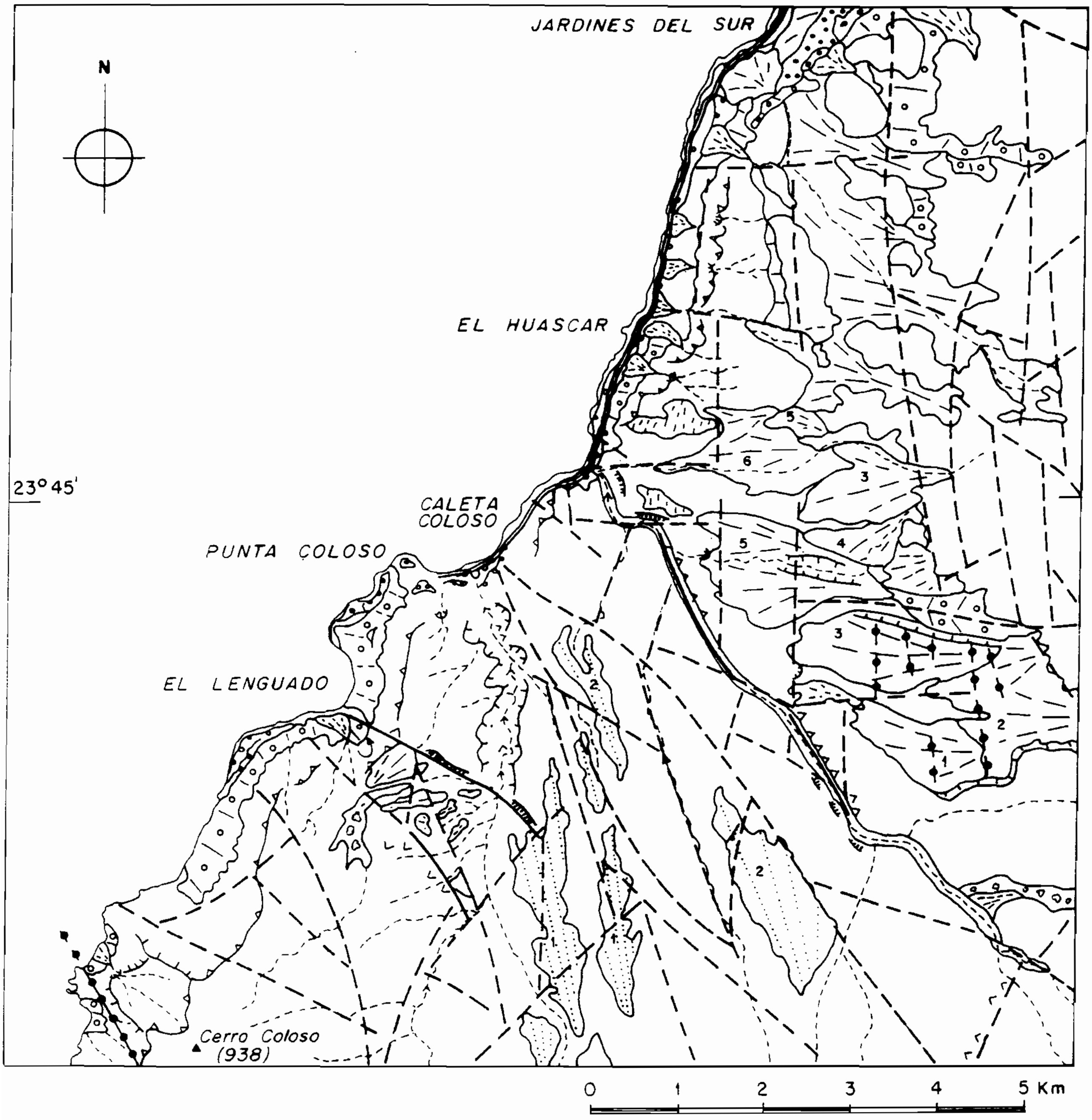
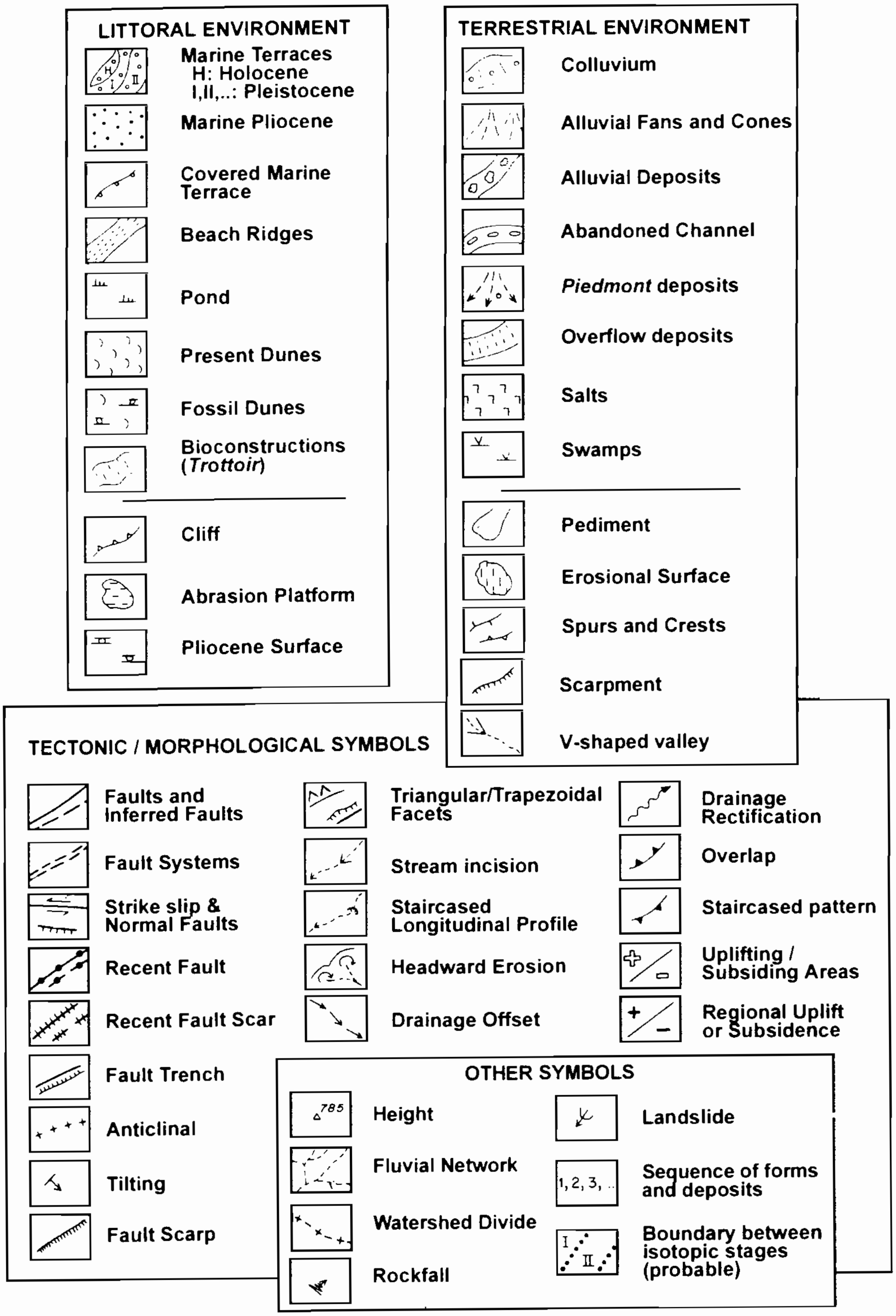


Fig. 0.1.6.- Photogeological sketch map of Caleta Coloso area, south of Antofagasta (see legend next page). Note sequence of alluvial fans and evidence for recent tectonic activity.

GENERAL LEGEND
(GEOLOGICAL AND GEOMORPHOLOGICAL SKETCH)



General legend of Fig. 0.1.6. (and of a series of similar other figures throughout the fieldguide.)

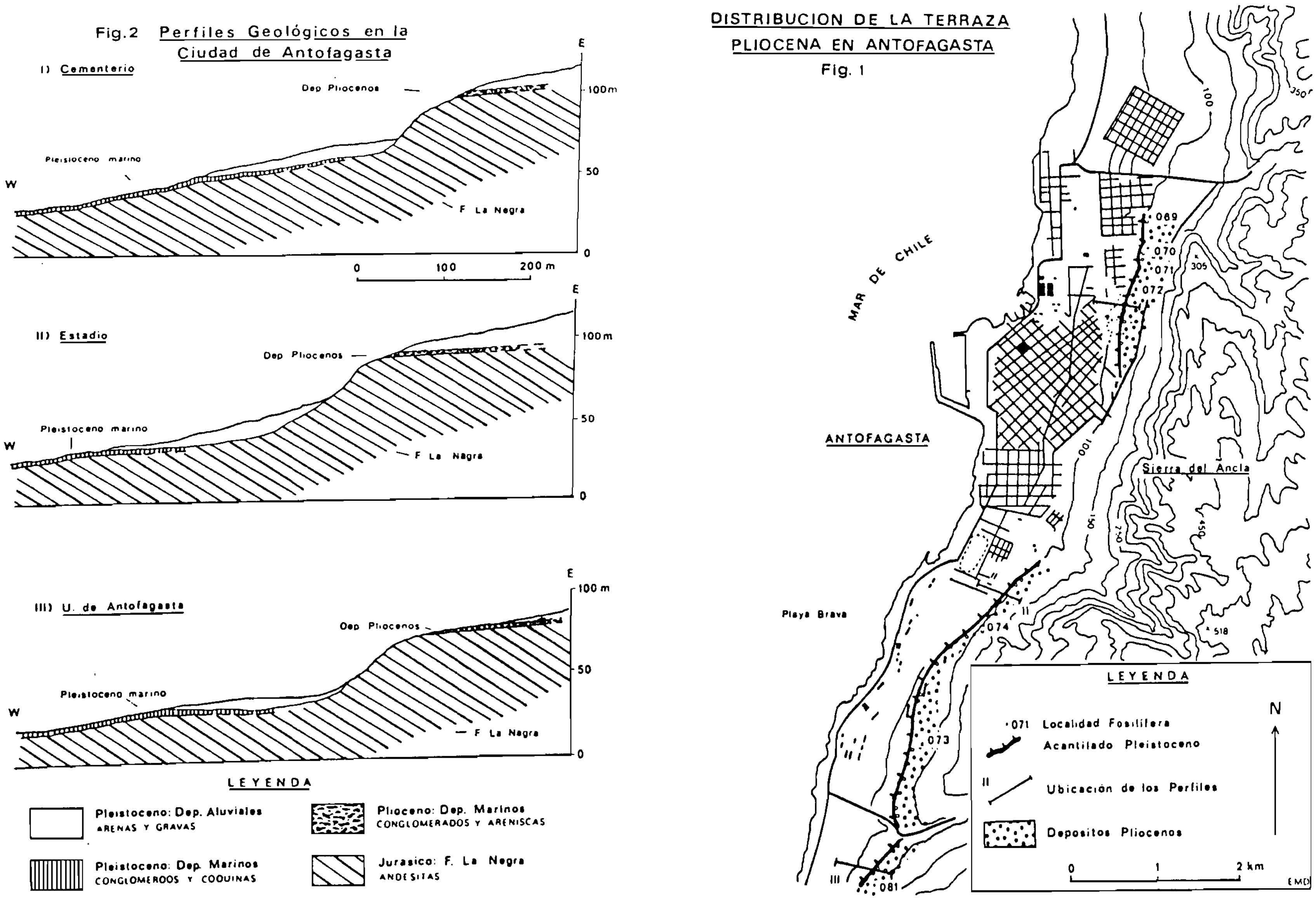


Fig. 0.1.7.- Distribution of remnants of the Antofagasta Terrace in Antofagasta, according to Martinez & Niemeyer (1982) who assigned a Pliocene age to this feature. Current research shows that, at least in some localities, a Pleistocene sea re-occupied the Pliocene terrace.

study on the ashes will be intented; meanwhile, it can be inferred that these ashes correlate with another outcrop of similar material, studied by Naranjo (1987) and dated 3 m.a. old, which is located across the Cordillera de la Costa, a few km north of Salar del Carmen, along the trace of the Atacama Fault zone. According to this tentative correlation, and taking into account the faunal composition and sedimentary facies of the coquina unit, the deposit sampled at Coviefi might be of Pliocene age. Nevertheless, a 2-3 m thick unit of coarse marine sediments overlies the thin coquina bed and contains a faunal assemblage which differs from that of the lower unit. It lacks the typical Pliocene elements (Chlamys), and the fragments of *Concholepas* resemble those of *C. concholepas* (Pleistocene-Holocene), not those of *C. nodosa* (Pliocene). It may be interpreted that the upper bed of coarse sediments corresponds to a Pleistocene marine unit that capped the Pliocene sediments, and which was exceptionally preserved in that locality.

Several other fossiliferous localities related to the Antofagasta Terrace were discovered uphill from the campus of Universidad de Antofagasta and immediately to the south and southeast of the residential area of Jardines del Sur. They are located at an elevation of +85 or +90 m, and present a fauna which strongly suggests a Pleistocene. At Coloso, at an elevation of ca.+80 m, the sediments overlying the marine platform provided fragmented and badly preserved mollusk shells. The composition of the Coloso fauna is very similar to that of Jardines del Sur and lacks elements which clearly indicate a Pliocene age. Like at the Coviefi locality, the fragments of the gastropod *Concholepas* are identified as belonging to the *C. concholepas* species, rather than to the *C. nodosa* species.

In conclusion, we infer that the Antofagasta Terrace was carved during a Pliocene high seastand, may be at the end of the Pliocene (if, as suggested by Herm, 1969, *Chlamys vidali* characterized the upper Pliocene). Nevertheless, the presence of Pleistocene marine deposits in a series of localities upon the terrace indicates that during the Early or early Middle Pleistocene, the sea reoccupied the Antofagasta Terrace. Possibly some erosional features of the terrace should be assigned to the effects of the last marine transgression (Pleistocene), and not to the previous (Pliocene) incursion.

Neotectonic implications of the new chronostratigraphic interpretation

The fact that the Antofagasta Terrace should not be viewed only as a Pliocene feature has tectonic implications. If, as we hypothesize, the sea reached the elevation of the previously carved marine platform, at some time in the first half of the Pleistocene (possibly the Early Pleistocene, within the lapse 1.6 - 0.7 My), this gives a useful indication for lateral correlation of the earliest Quaternary shoreline remnants.

If it is assumed that the sea level was close to the present datum during the early Pleistocene, the inferred mean uplift rate of the Antofagasta can be evaluated to a grossly approximated figure of 100 mm/10^3 yr (100 m uplift in 1,000,000 yr ±300,000). Whatever the true age of the remnants of the Pleistocene transgression, the new chronologic interpretation implies that the coastal uplift was stronger than previously supposed.

On our way to the second stop, through the Quebrada La Negra, there will be some oportunities to see remnants of the mud-flows (« aluviones ») provoked by the 40 mm rainfall which occureed on June 18, 1991 (Fig. 0.1.8).

Fig. 0.1.8.- Destruction by the mud-flows consecutive to the June 18, 1991 rainfall. Photograph (G.Vargas) taken from the base of the coastal range toward the bay of Antofagasta.

THE SALAR DEL CARMEN FAULT

From the road between Antofagasta and the Panamerican Highway, the fieldparty will observe the escarpment of the Salar del Carmen fault, a component of the Atacama Fault Zone which presents the most recent activity of the whole system. The escarpment is a few m high. It does not show a strong erosion, and might be interpreted as young as Holocene or late Pleistocene. Actually, the discussion regarding the age of the last motion on this fault is still open. The morphological and sedimentological features of the alluvial fans, on this particular side of the Cordillera de la Costa (with still less rain than along the coast) suggest that the last activity may be as old as the late Middle Pleistocene (more than 150,000 yr, and less than 0,5 m.a.).

Atacama Fault Zone

The Atacama Fault Zone is a major, 1100 km long, structural feature, oriented N-S, between Iquique (20° 30'S) and La Serena (29° 30'S) located on the eastern flank of the Cordillera de la Costa. It is composed of two segments separated by the NW-SE oriented Taltal Fault (Fig.0.2.1).

Discussion on the age and motion of the AFZ

The determination of the age of the activity and precise motion originated many discussions and controversies in the Chilean geological literature of the last half-century.

St Amand & Allen (1960) were the first authors, in modern times, to study the Atacama Fault Zone (= AFZ). They distinguished two major sectors, between Iquique and Taltal, and between Talatal and La Serena, but viewed the Atacama Fault System as a single one, which had essentially a strike-slip motion. In 1961, Bowes et al. considered that both sectors corresponded to two distinct strike-slip faults which would have moved in opposite directions. Then, Arabasz (1968, 1971) considered that the AFZ was one single mega-feature, and interpreted that its main activity began in Mesozoic times when it would have had a strong strike-slip motion (displacement of tens of km?); in Quaternary times, the activity of the system would have been essentially dip-slip, although Arabasz could not detect any significant microseismicity that could be associated to these recent motions. Later, Scheuber (1987) determined in the sector north of Paposo, that two stages could be distinguished in the Mesozoic strike-slip history of the AFZ: one during the late Jurassic and the other in early Cretaceous. These motions would have been sinistral. In the late Miocene, the AFZ would have been reactivated by dip-slip motions which would have uplifted the western block. The last two phases of activity were radiometrically dated by Hervé (1987a, 1987b) as 144 -131 Ma, and 19 - 5.5 Ma. This author suggested that the last activity of the AFZ would have occurred in the Miocene.

In 1987, Naranjo interpreted that the last motions along the fault were dip-slip displacement that occurred before the late Miocene (possibly the late-Middle Miocene). The linear escarpment which can be seen in the area of Salar del Carmen (E of Antofagasta) would correspond, he suggested, to local and superficial deformations (gravitational

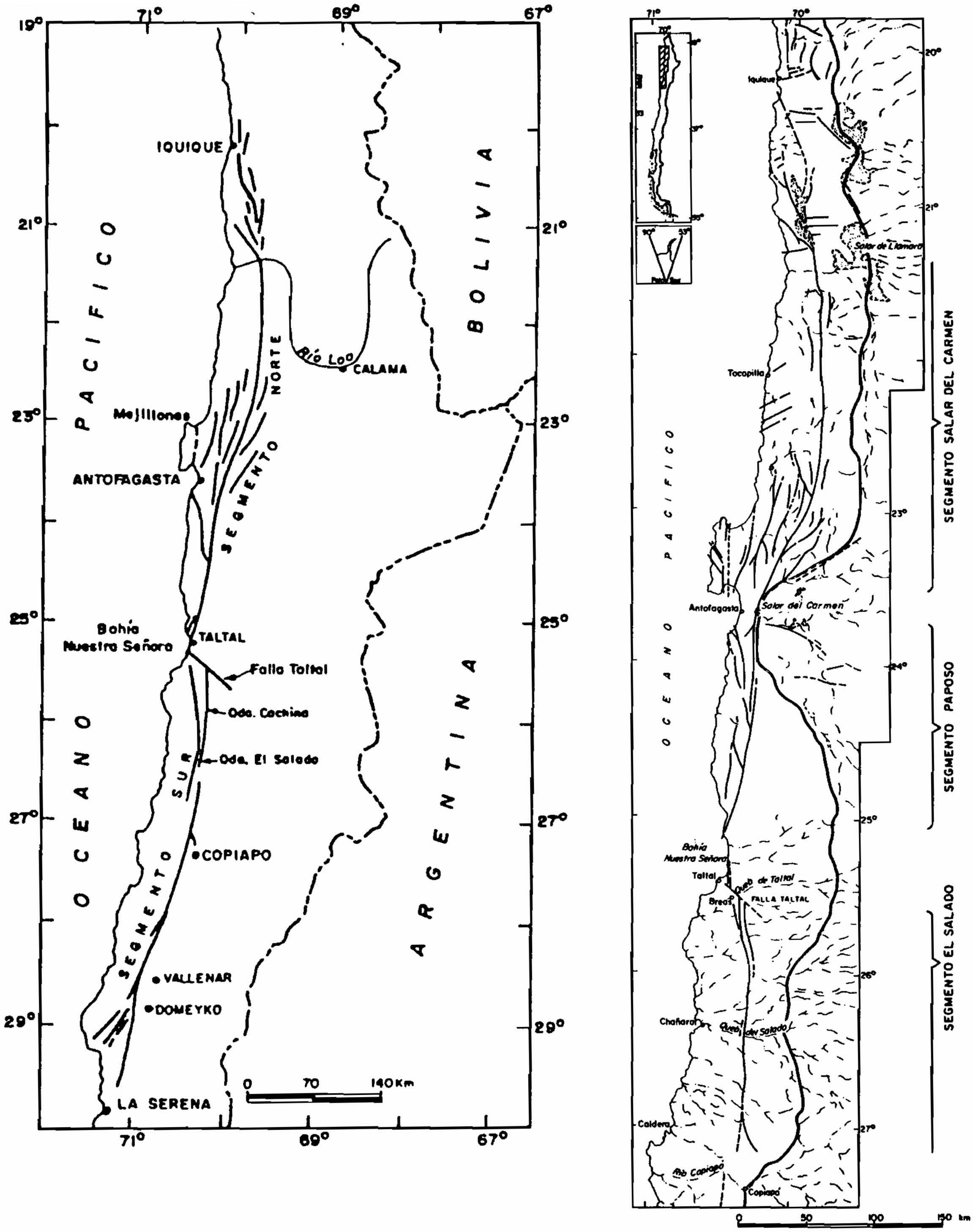


Fig. 0.2.1.- The Atacama Fault Zone according to Hervé & Thiele (1987)(left) and Naranjo (1987)(right): two branches are distinguished, north and south of Taltal.

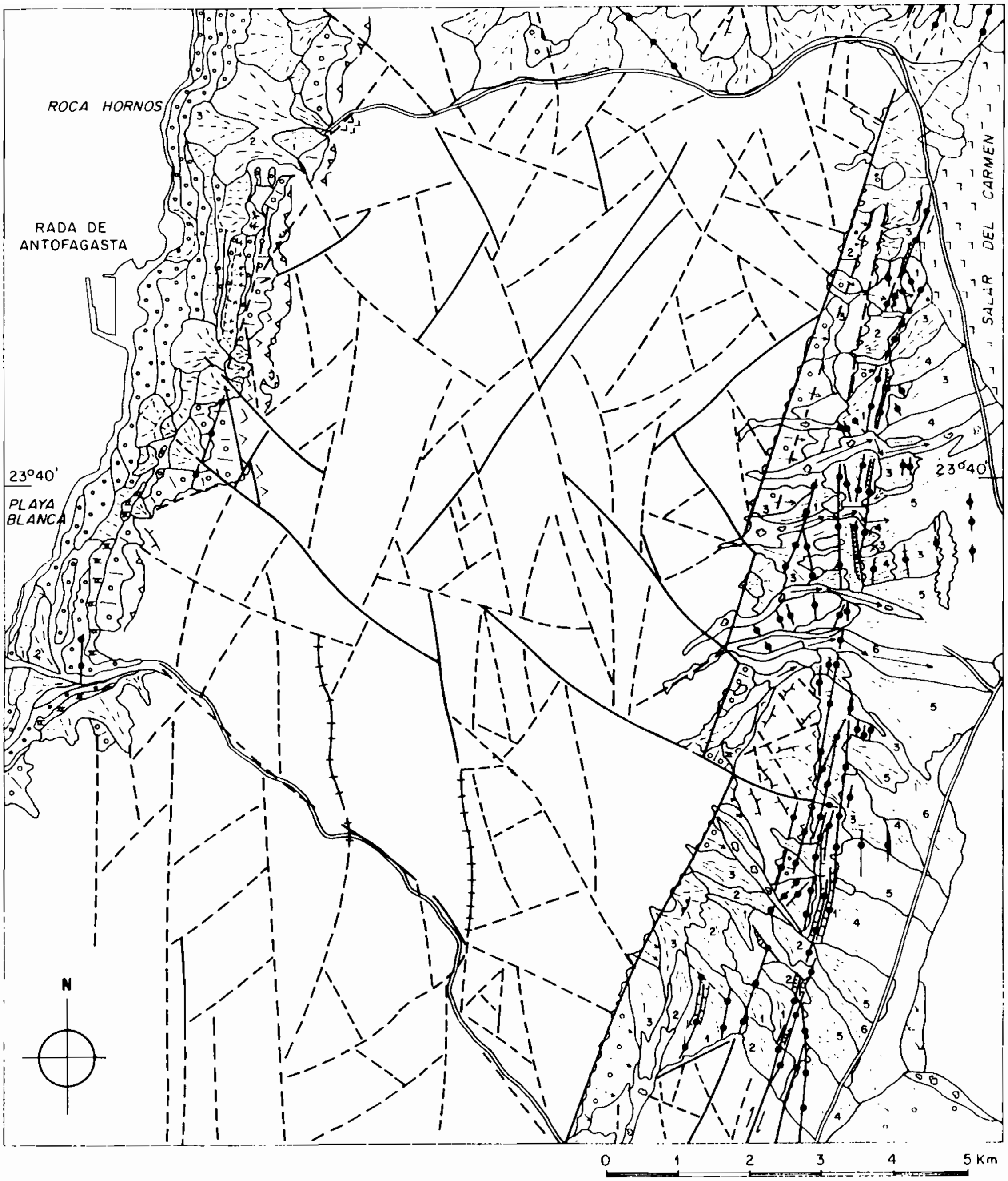
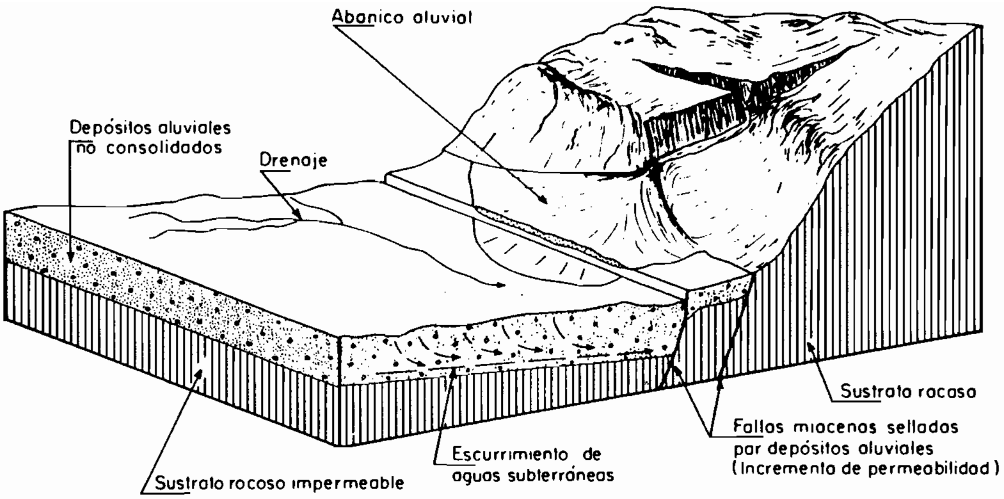
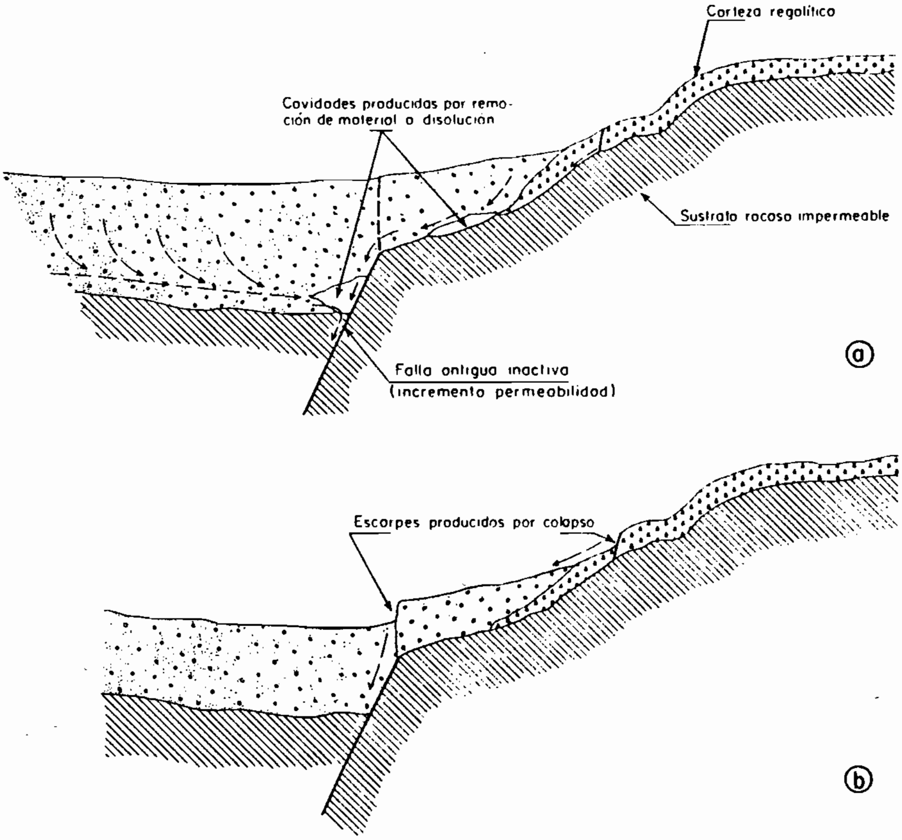


Fig. 0.2.2. - Photogeological sketch map of the sector of the Salar del Carmen fault, with indication of the most recent evidence of motion (see legend of Fig. 0.1.6).





Diagramas explicativos para la formación de escarpes: Se produce un incremento de la permeabilidad de las aguas subterráneas a través de fallas antiguas inactivas, lo que permitiría una mayor disolución y remoción de materiales finos (sales) (a). Los escarpes en el aluvio serían el efecto de colapso gravitacional de los depósitos no consolidados (b).

Fig. 0.2.3.- Interpretation of gravitational slides under the action of circulating water along old fault planes, as proposed by Naranjo (1987), for the Salar del Carmen Fault..

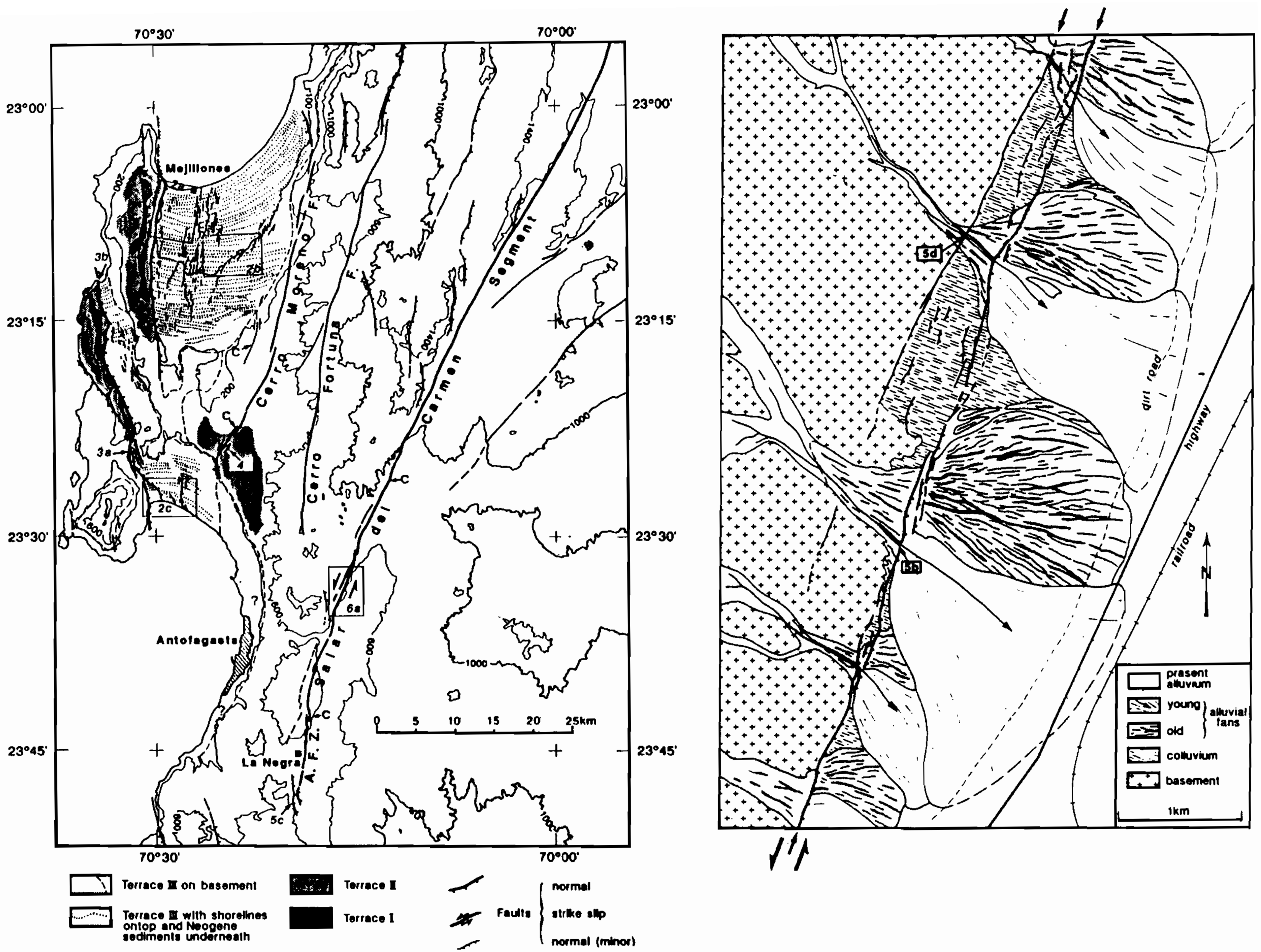


Fig. 0.2.4.- The Salar del Carmen sector of the Atacama Fault system, in the regional neotectonic framework, according of Armijo & Thiele (1990). To the right a photo-interpretation of « recent » sinistral activity of the fault.

collapses) related to groundwater circulation (Fig. 0.2.3). According to Naranjo (1987), the AFZ would be an old fracture zone along which the apparent features of reactivation would, in fact, be due to surficial phenomena more related with climatic, pedological and hydrological parameters than to thectonic. Later, Armijo & Thiele (1990) stressed that the AFZ was active in the Quaternary, and that it recorded a left-lateral strike-slip motion. This interpretation was mainly based upon the offsets observed on alluvial fans north of Salar del Carmen (Fig. 0.2.4). They proposed two explanations for this recent strike-slip activity: the left-lateral motion observed in the mentioned locality may be related to local geometrical factors and to the regional E-W extension (in a context of right-lateral strike-slip motion), or the fault would be left-lateral and would pertain to a sub-continental system involving the Santa Cruz (eastern Bolivia) bend.

LATE QUATERNARY COASTAL CHANGES IN NORTHERN CHILE

Guidebook for a fieldtrip
(Antofagasta-Iquique, 23-25 november 1995)

organized during the 1995 Annual meeting of the
International Geological Correlation Program Project 367
(19-28 November, Antofagasta, Chile)

First day of Fieldtrip

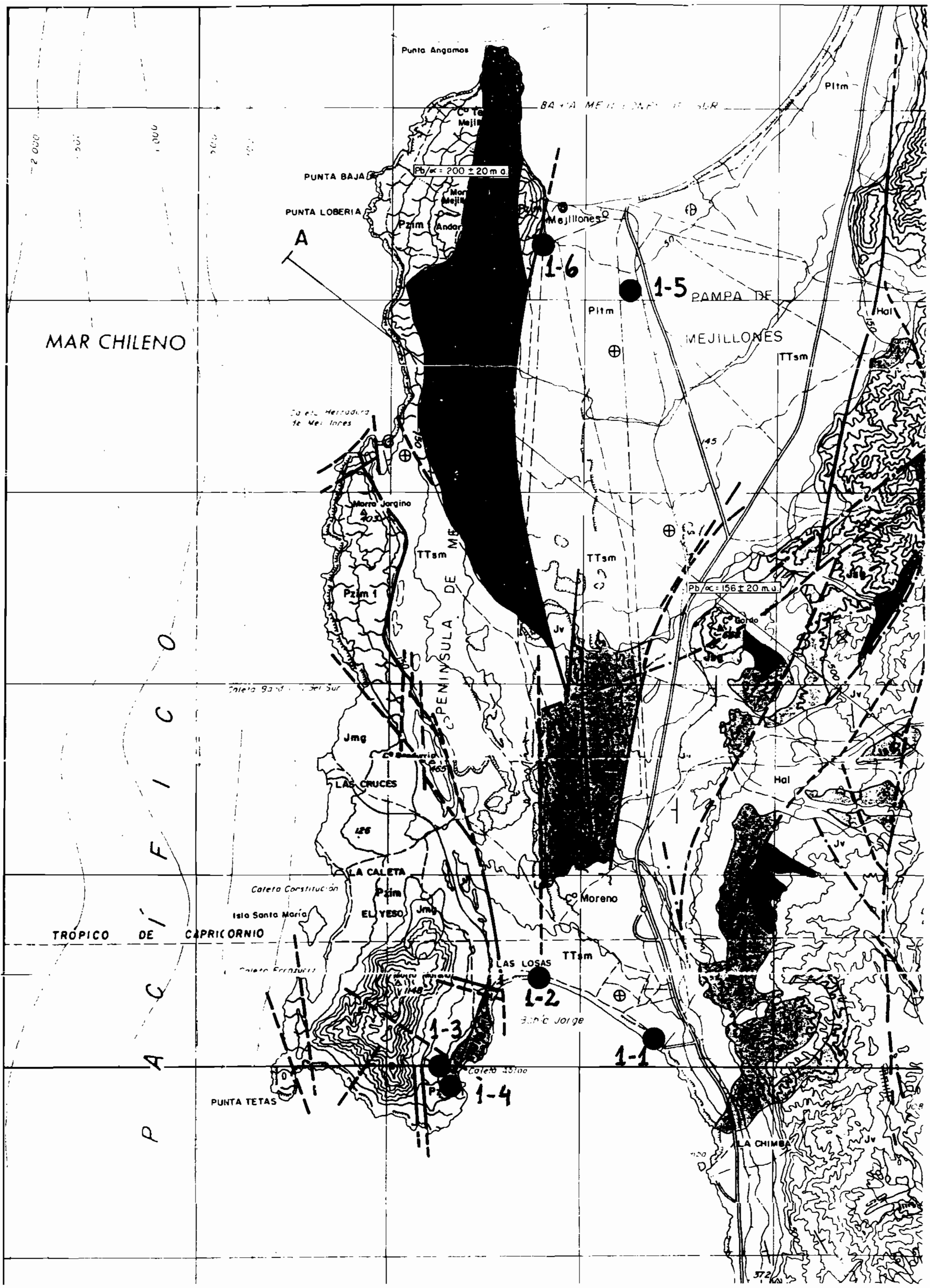


Fig. 1.0.1.- Localisation of the stops of the first day of fieldtrip, between Antofagasta and Mejillones. (Fragment of the geological map of Antofagasta, Ferraris & Di Biase, 1978).

THE PLIOCENE LA PORTADA FORMATION

At the first stop (Fig. 1.1.1), will be examined the Pliocene La Portada Formation and the marine terrace assigned to the isotopic stage 9 (300 ka). Furthermore we shall comment some aspects of the Late Cenozoic regional stratigraphy.

The stratigraphic section of La Portada

The Formation La Portada is the 40 m thick sequence of yellowish shelly sandstone which unconformably overlies the Jurassic La Negra Fm (Fig. 1.1.2). At the base, the sediments show shoreface and foreshore facies. Near the top of the sequence reworked alluvial coarse material can be found in interstratified layers. The shell fragments consist almost exclusively of barnacle (Fig. 1.1.3). The whole sequence corresponds to a shallow nearshore unit.

The La Portada Fm is covered by marine sands of Pleistocene age. These younger nearshore fossiliferous sediments are in turn underlying Quaternary alluvium. The top of the stratigraphic sequence at La Portada consists of Holocene dunes accumulated atop the edge of the seacliff.

La Portada Formation

Brüggen (1950) assigned a Pliocene age to the marine sedimentary sequence that crops out in the Peninsula of Mejillones. On paleontological grounds, Herm (1969) correlated part of the marine sediments of the Mejillones peninsula with the Coquimbo Fm and some marine terrace deposits studied in La Serena area (Fig. 1.1.3) . In 1978, Martinez found Middle-Late Miocene foraminifers in a sedimentary unit at Caleta Heradura de Mejillones. In the geological map of Antofagasta (Fig. 1.0.1, 1.1.1), Ferraris & Di Biase (1978) formally defined the La Portada Fm as a Mio-Pliocene complex marine unit. Finally, Krebs et al. (1992) restricted the La Portada Fm to the Pliocene part of the marine sequence outcropping in the peninsula (Fig. 1.1.5).

The La Portada Formation is correlated with the oldest deposits found upon the Antofagasta Terrace (Martinez & Niemeyer, 1982). From the existence of *Chlamys vidali,* in both localities it may be inferred that they are at least in part of Late Pliocene age.

Late Cenozoic regional stratigraphy

At Caleta Herradura de Mejillones, in the northwestern part of the Mejillones Peninsula (Fig. 1.0.1), an outstanding statigraphic section is preserved. This section shows a major unconformity between Miocene and supposedly Pliocene marine sediments (Fig. 1.1.4). The Miocene part of the section was studied by Krebs et al. (1992) who defined the Formation Caleta Herradura. The Caleta Herradura Fm sediments include nearshore facies and offshore pelagic sequences (with diatomite).

In the upper part of the region chronostratigraphy, some authors refer to a Mejillones Formation of Pleistocene age (Ferraris & Di Biase, 1978; Flint et al., 1991; Hartley & Jolley, 1995) (Fig. 1.1.5, 1.1.6). There is a stratigraphic problem regarding this so-called

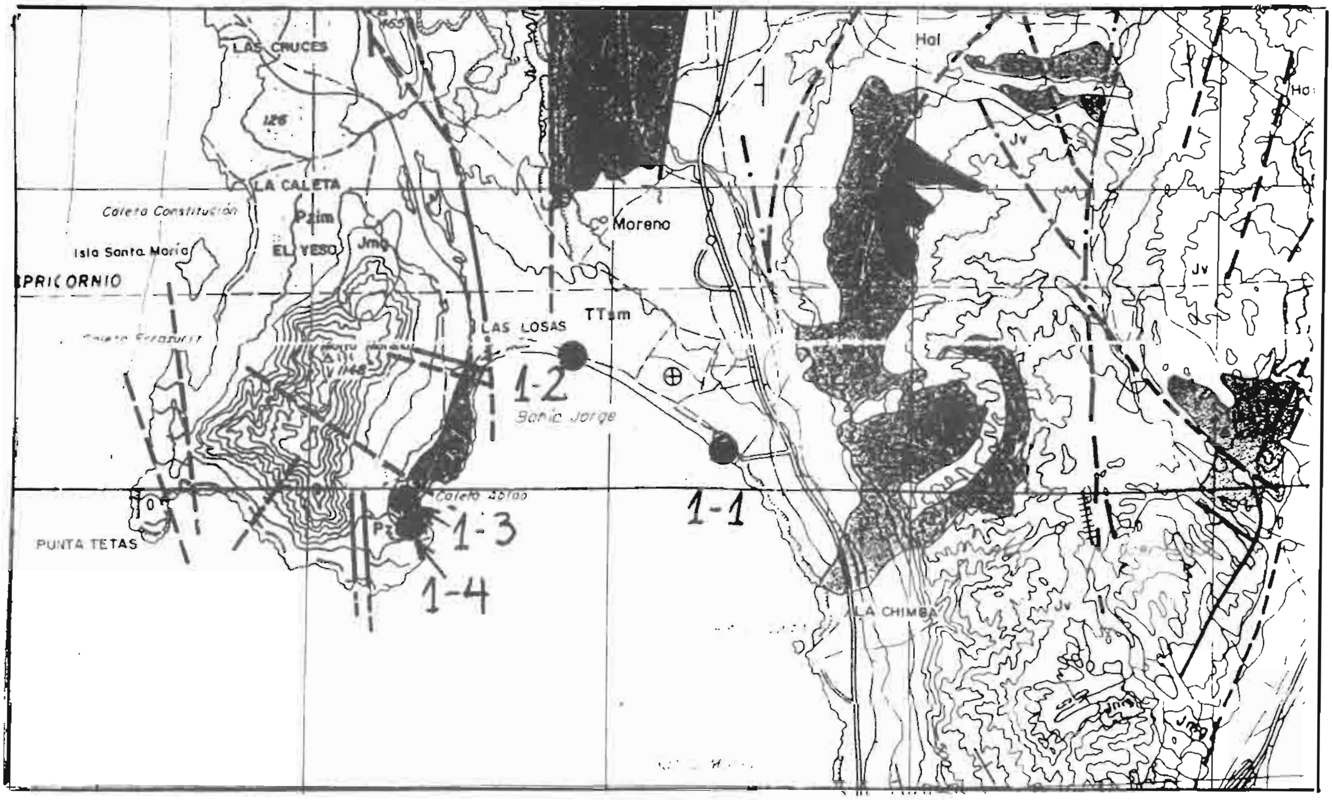


Fig. 1.1.1.- Localisation of the first stops of the first day of fieldtrip, along the northern shores of Antofagasta bay.

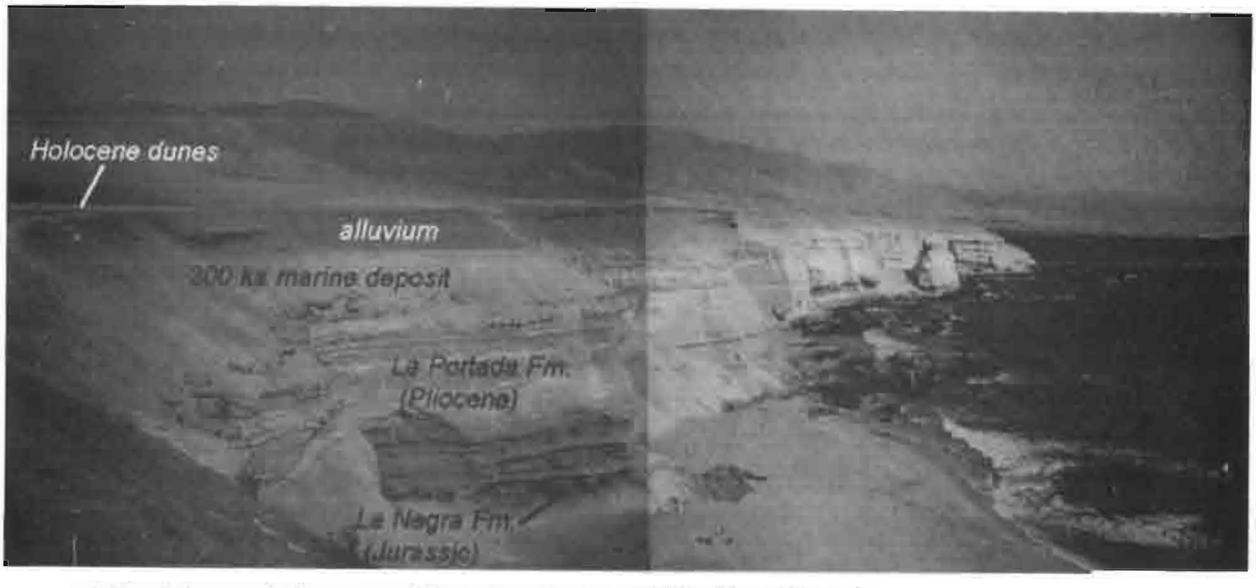


Fig. 1.1.2.- View of the seacliff at La Portada (Photo L.O.). From top to bottom, one can distinguish:

- a Holocene eolian sand cover;
- Late and late-Middle Pleistocene alluvium;
- Middle Pleistocene marine terrace deposit (whitish unit);
- the Pliocene La Portada Formation ;
- the Jurassic substrate (dark lavas of La Negra Formation).

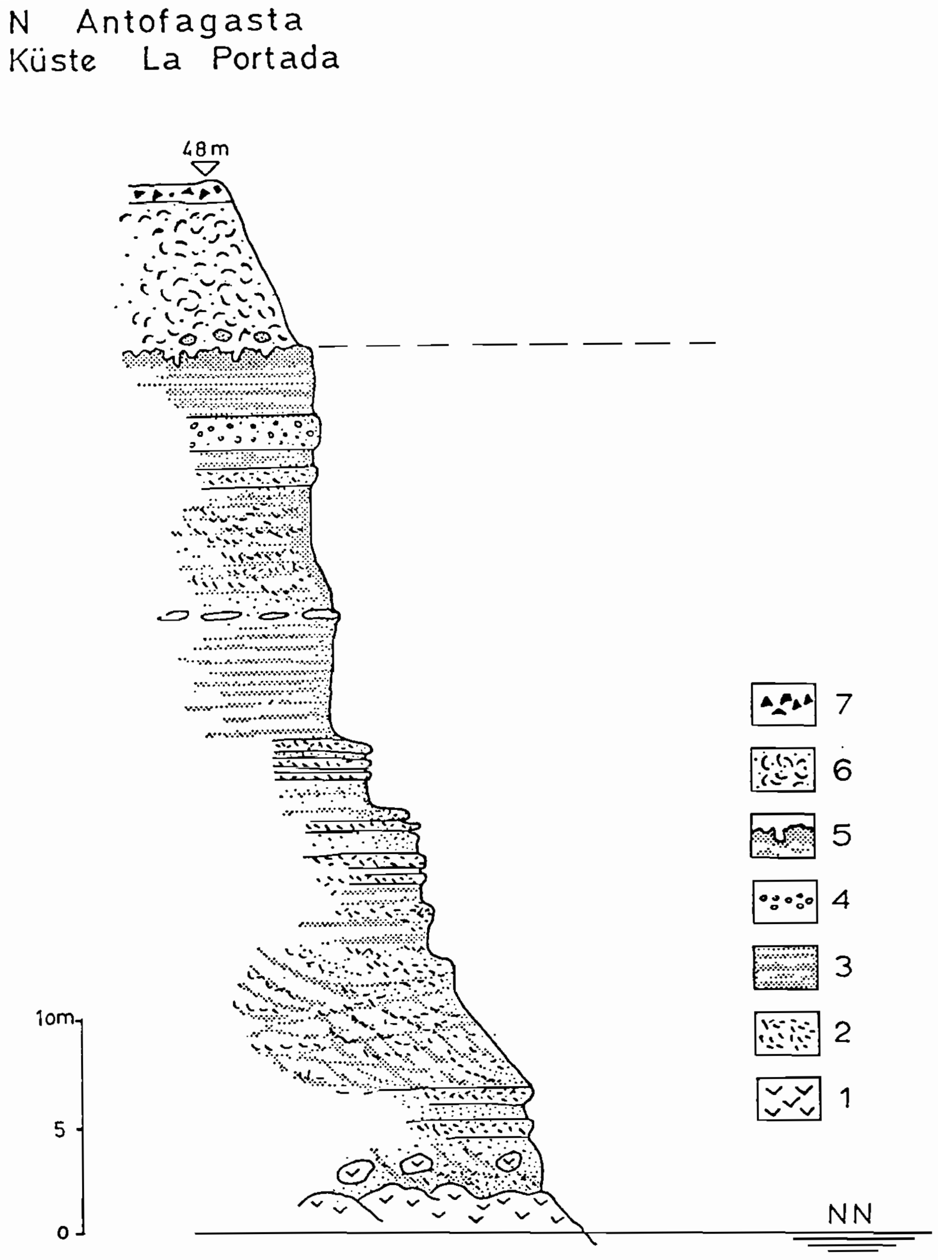


Abb. 4: Profil an der Steilküste nördlich Antofagasta beim Aussichtspunkt „La Portada":

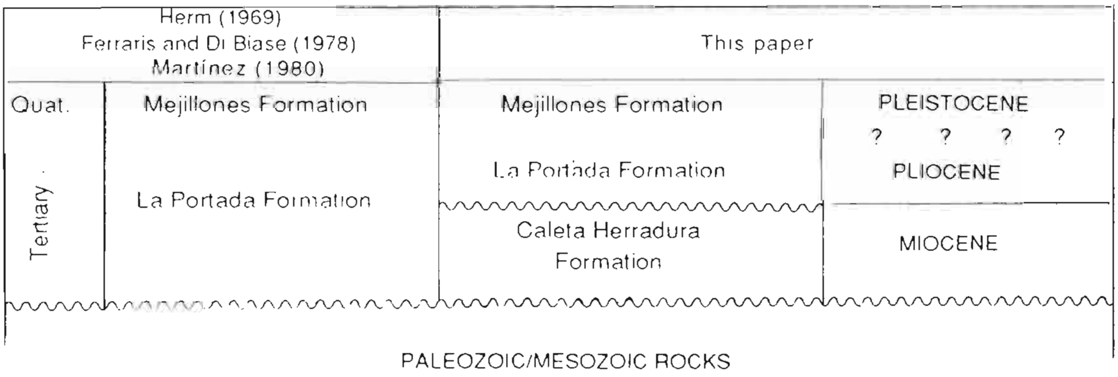
1) Jurassische und kretazische, porphyritische Ergußgesteine;
2) Grober Schill, vorwiegend aus Balanus-Fragmenten bestehend, kreuzgeschichtet oder in kompakten Bänken, bis 1,5 m mächtig;
3) Gelbliche Feinsande, feingeschichtet mit Schilleinschaltungen;
4) Grobsande bis Feinkonglomerate;
5) Graue, grünliche Sande, zementiert mit sark angelöster und kavernöser, unregelmäßiger Oberfläche;

2—5 = Pliozän.

6) Grobe Strandsande mit grobem Muschelschill, der lagenweise in wechselnder Korngröße dichtgepackt das Sediment nahezu ausschließlich aufbaut (Altpleistozän);
7) Eckiger Schutt der hier auslaufenden Schuttkegel, mit Flugsand gemischt.

Fig. 1.1.3.- Geological section of the seacliff at La Portada (from Herm, 1969).

Fig. 1.1.4.- View of the western part of the bay of Herradura de Mejillones, showing the unconformity between the Miocene Caleta Herradura Fm and the Pliocene La Portada Fm (Photo L.O.). The unconformity is immediately above the white diatomite bed assigned to the end of the Miocene.



Herm (1969) Ferraris and Di Biase (1978) Martínez (1980)		This paper	
Quat.	Mejillones Formation	Mejillones Formation	PLEISTOCENE
			? ? ? ?
Tertiary	La Portada Formation	La Portada Formation	PLIOCENE
		Caleta Herradura Formation	MIOCENE
PALEOZOIC/MESOZOIC ROCKS			

Fig. 1.1.5.- Chronostratigraphic interpretations of the Mejillones, La Portada, and Caleta Herradura formations (from Krebs et al., 1992).

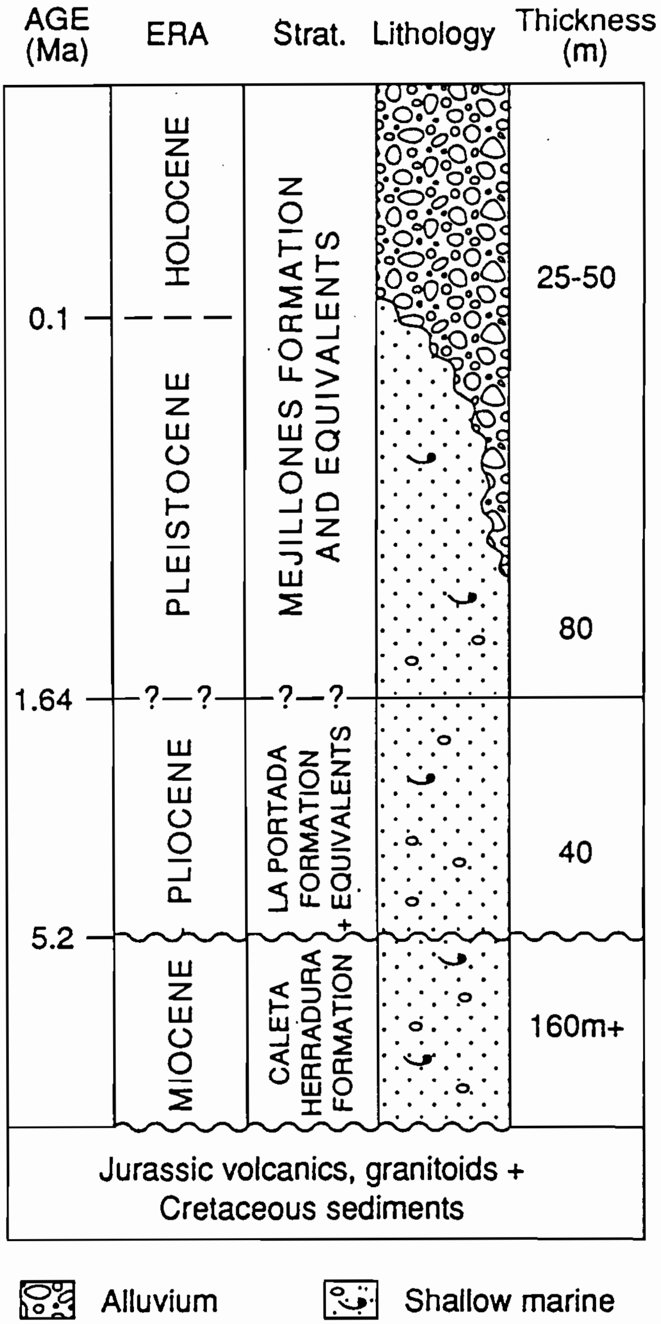


Fig. 1.1.6.- Regional Cenozoic stratigraphy in the Mejillones Peninsula area used by Hartley & Jolley (1994) and other authors.

formation since it refers to Pleistocene marine terrace deposits which cannot be considered as a continuous sequence. Ferraris & Di Biase (1978) defined this « formation » as a sequence of marine sediments, up to 80 m thick, which crop out in the northern part of Pampa de Mejillones and in the Hornitos area (Fig. 1.0.1). It is misleading to consider the thin coastal deposits (usually 1 to 2 m thick) associated with the successive interglacial transgressions of the last million years or so, as a formation which would have an 80 m thickness.

GEOCHRONOLOGY OF THE 300 ka MARINE TERRACE

The Middle Pleistocene marine terrace

The nearshore sediments accumulated upon the La Portada Fm are loosely consolidated sands, locally rich in well-preserved shells (*Mulinia* cf *M. edulis* and *Mesodesma donacium* predominant). New geochronological data were obtained on shells of the deposit:

C92-38 (+28 m)

Mulinia cf *M edulis*:	A/I: 0.66 ± 0.10 (n=12)
Mesodesma donacium	A/I: 0.67 ± 0.12 (n=11)

U-series dating and aminostratigraphic results suggest a ca. 300,000 yr age:

C92-39 (+28 m)

Mulinia cf *M. edulis*:	U/Th (TIMS):	282 ± 9 ka
Mesodesma donacium	U/Th (α):	275 ± 11 ka
« «	«	288 ± 12 ka

The alluvial cover of the marine unit is several meters thick, and consists of two or three sub-units. It is inferred that these alluvial layers were deposited in the last three glacial/interglacial cycles. In some cases, a thin bed of eolian sand separates the alluvial sub-units (Fig. 1.1.7).

Toward the west of La Portada, the Pleistocene marine deposit associated to the marine terrace is progressively more cemented (Fig. 1.1.8.)

Current research aims at correlating the La Portada marine terrace with the wave-cut platforms that are preserved in the northern and most recent suburbs of Antofagasta (Fig. 1.0.2 & 1.0.3).

Fig. 1.1.7.- Two thin eolian sandy units interstratified in the alluvial deposits that cover the nearshore sediments of the 300 ka marine terrace (see Table 1.1.1), afew km SE of La Portada locality. The eolian layers may be related to the ca. 200 ka and 120 ka interglacial episodes.

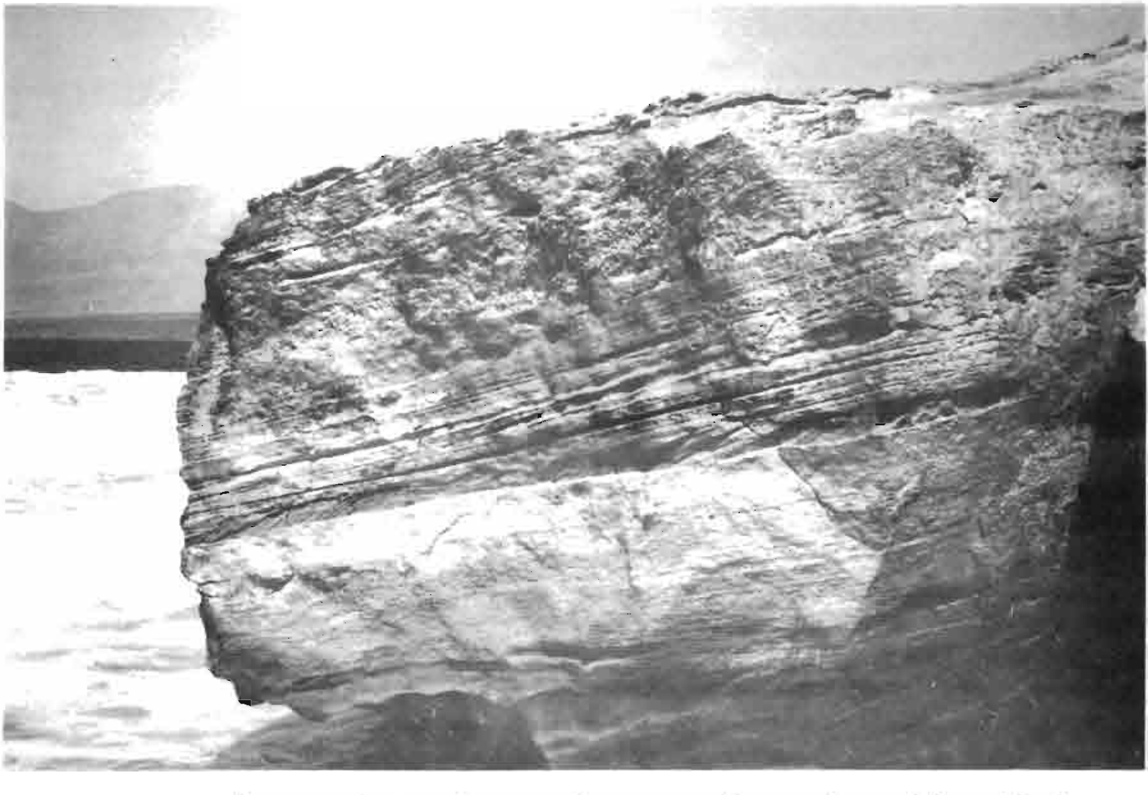


Fig. 1.1.8.- Upper shore and shoreface sedimentary figures in a fallen block from the Pleistocene marine terrace unit which overlies the La Portada Fm., at Las Lozas (see Stop 1-2).

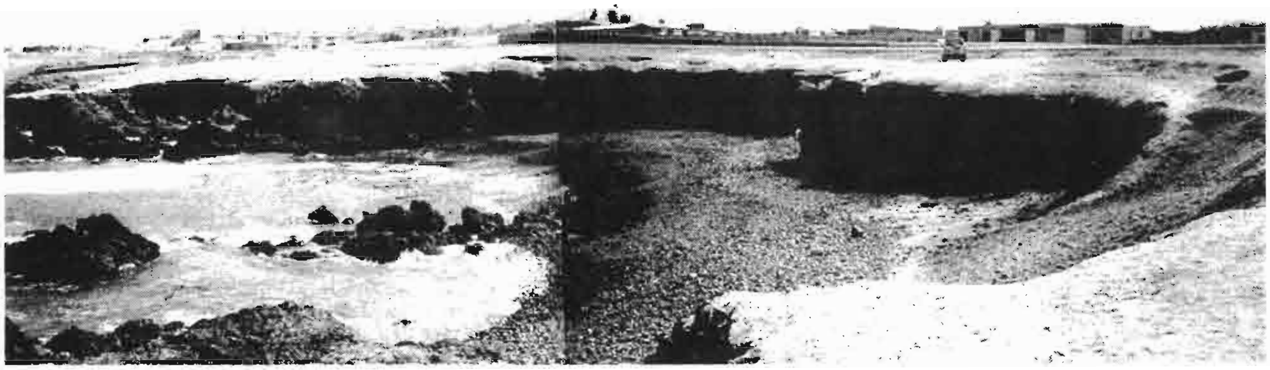


Fig. 1.0.2.- Wave-cut platform carved during a high seastand of the last interglacial (probably IS 5e, according aminoacid data) near Playa Trocadero (north of Antofagasta).

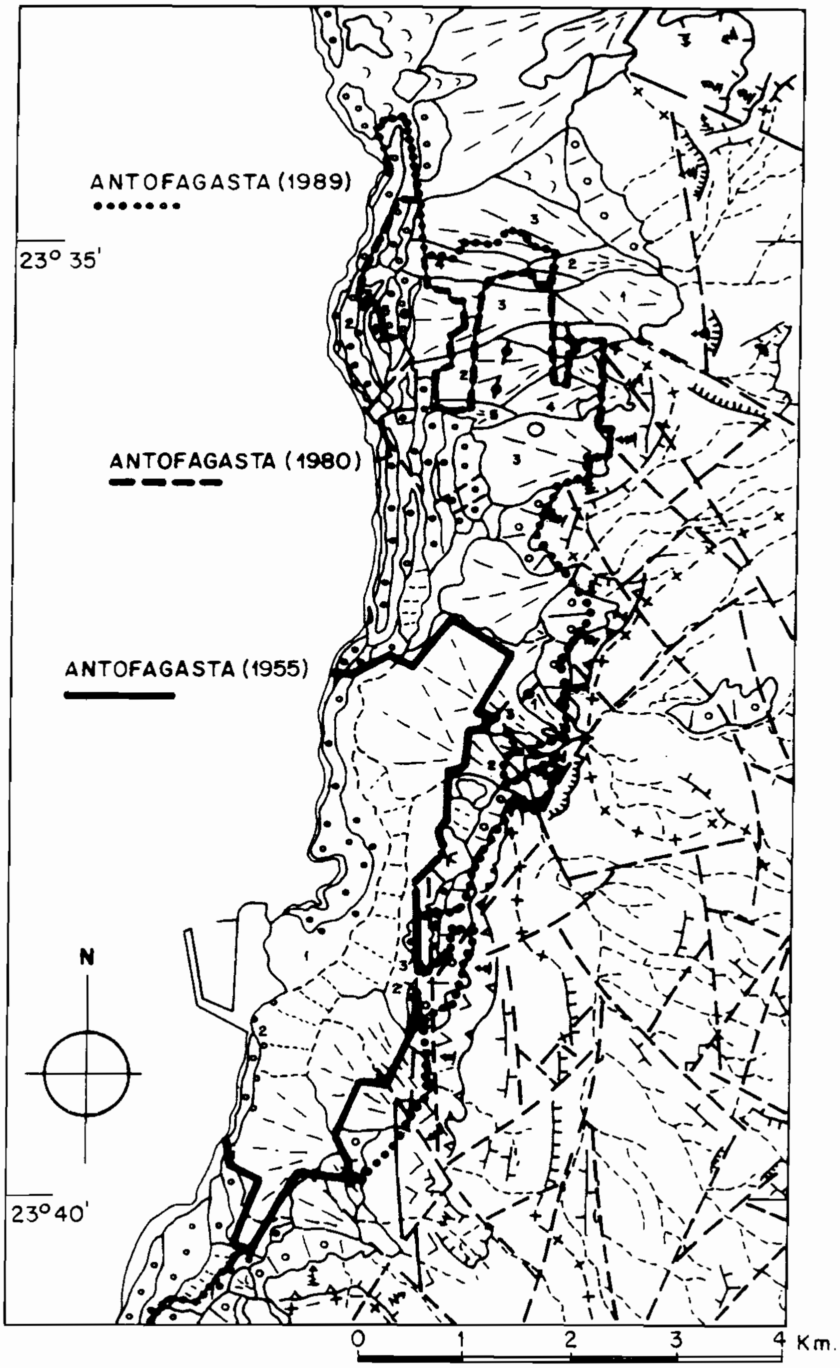


Fig. 1.0.3.- Geological sketch map of northern Antofagasta (see legend of Fig. 0.1.b). Up to five marine terraces and abraded platforms can locally be distinguished in the recently urbanized parts of the city.

NEOTECTONICS IN THE SOUTHERN MEJILLONES PENINSULA

At Stop 1-2 will be discussed several aspects of neotectonic deformation in the southern part of Mejillones Peninsula, by looking at fault scarps and considering long-term uplift motions that produced series of beach ridges.

Fractures along the edge of the seacliff: the 1995 earthquake

On the edge of the sea cliff, all along the northern bay, a series of open fractures appeared after the July 30, 1995 Antofagasta earthquake (Fig.1.2.1). They do not represent the faulting activity itself, but reflect local readjustments and secondary effects of gravity sliding downcliff. In several places, large blocks of the cliff edge were tilted or fell down onto the beach (Fig. 1.2.1 & 1.2.2).

Faulted Middle Pleistocene marine terraces

Along the northern coast of the bay of Antofagasta, from La Portada westwards, the attitude of the seacliff indicates a general tilting towards the west. A series of normal faults with downthrown blocks towards the west that cut the marine terrace and its Pliocene substrate, are visible along the seacliff. Between Las Lozas and La Rinconada, in the NW extremity of the bay, the cemented Pleistocene sandstone unit (Fig.1.1.8) dips below the modern beach ridge and below sea level.

At La Rinconada, a major crustal fault separates an eastern semi-graben from the uplifted Cerro Moreno block (Fig.1.2.3 & 1.2.4). The La Rinconada fault shows several lines of evidence of relatively recent (Holocene ?) activity.

At Stop 1-2, will be shown a graben structure with surface scarps several metres high (Fig.1.2.4). In the cliff, fault offsets of up to 6 m were measured (Armijo & Thiele, 1990; see upper photograph of Fig. 1.2.2, taken before the 1995 earthquake). Such normal faults belong to a complex en échelon system, which associates NNW-SSW and N-S fractures (Fig. 1.2.4).

Neotectonic behaviour of the Pampa del Aeropuerto

Another striking particularity of the southern part of the isthmus of the Mejillones Peninsula is the series of emerged beach ridges that extends from the present coastal cliff up to an elevation of +200 m. These beach ridges are so well preserved, that they display former beach cusps which have a very similar expression on aerial photographs to the present ones (Fig. 1.2.5). As a whole, the sequence of parallel emerged shorelines tends to indicate that the whole plain has been emerging without major internal deformation, at least before the formation of the youngest beach ridge (presently close to the seacliff).

The age of the oldest shorelines of the sequence, and the duration of the forming-processes of the series of beach ridges is still a matter of discussion. This problem, at the regional level, will be examined later, at Stop 1-5. Nevertheless it may be considered here

Fig. 1.2.1.- To the west of La Portada, evidence of superficial fracture and gravity sliding along the edge of the seacliff, produced by the July 30, 1995 earthquake.

Fig. 1.2.2.- Some evidence of the effects of the Antofagasta earthquake in the seacliff of the northern Antofagasta bay: a large (previously) faulted block (center of photograph) fell down as a consequence of the shaking motions that occurred on July 30, 1995 . (Photos L.O.). Above: before, and below: after the earthkquake.

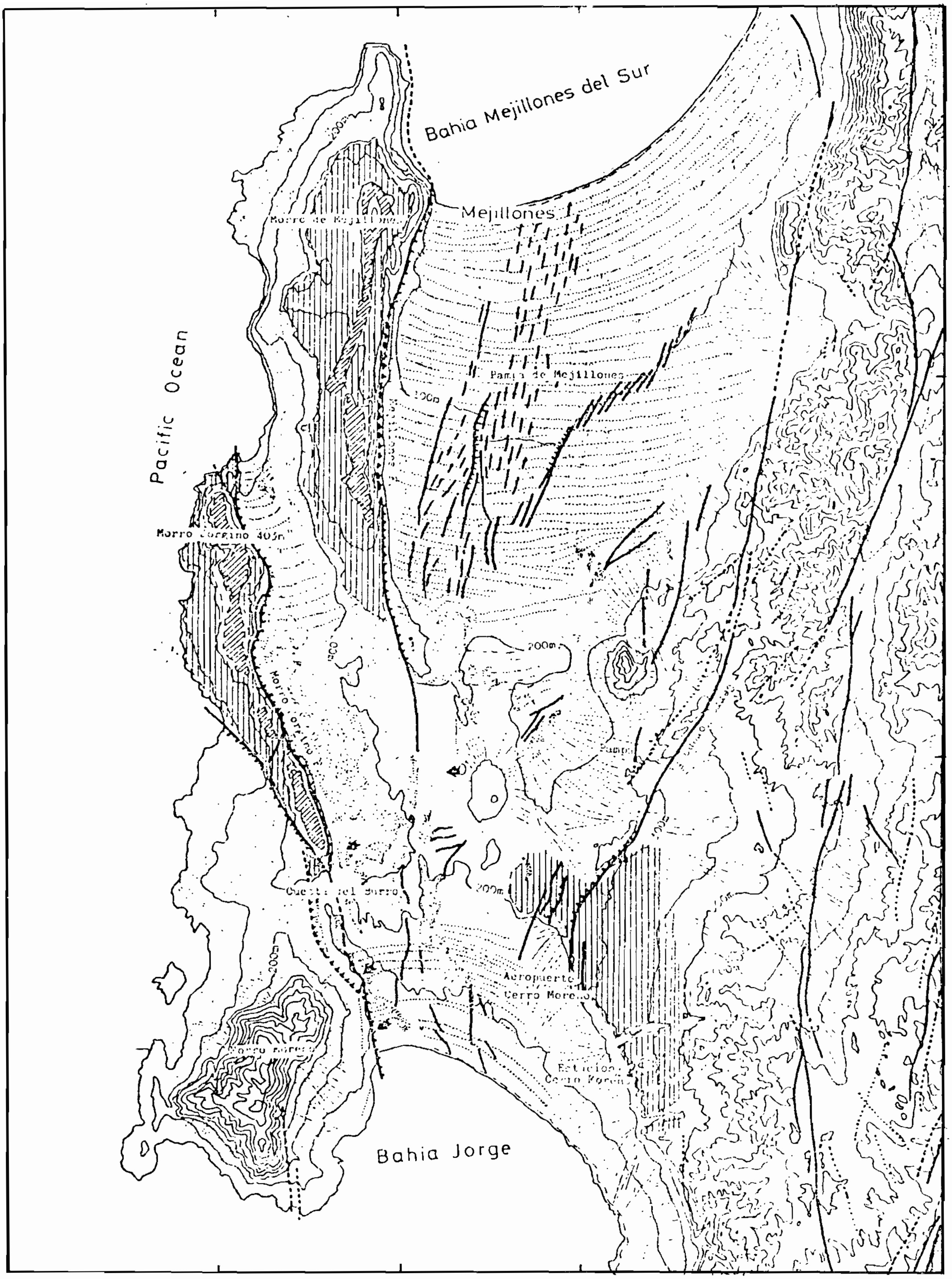


Fig. 1.2.3.- Sketch map of Quaternary faults and structures of the Mejillones Peninsula, according to Okada (1971).

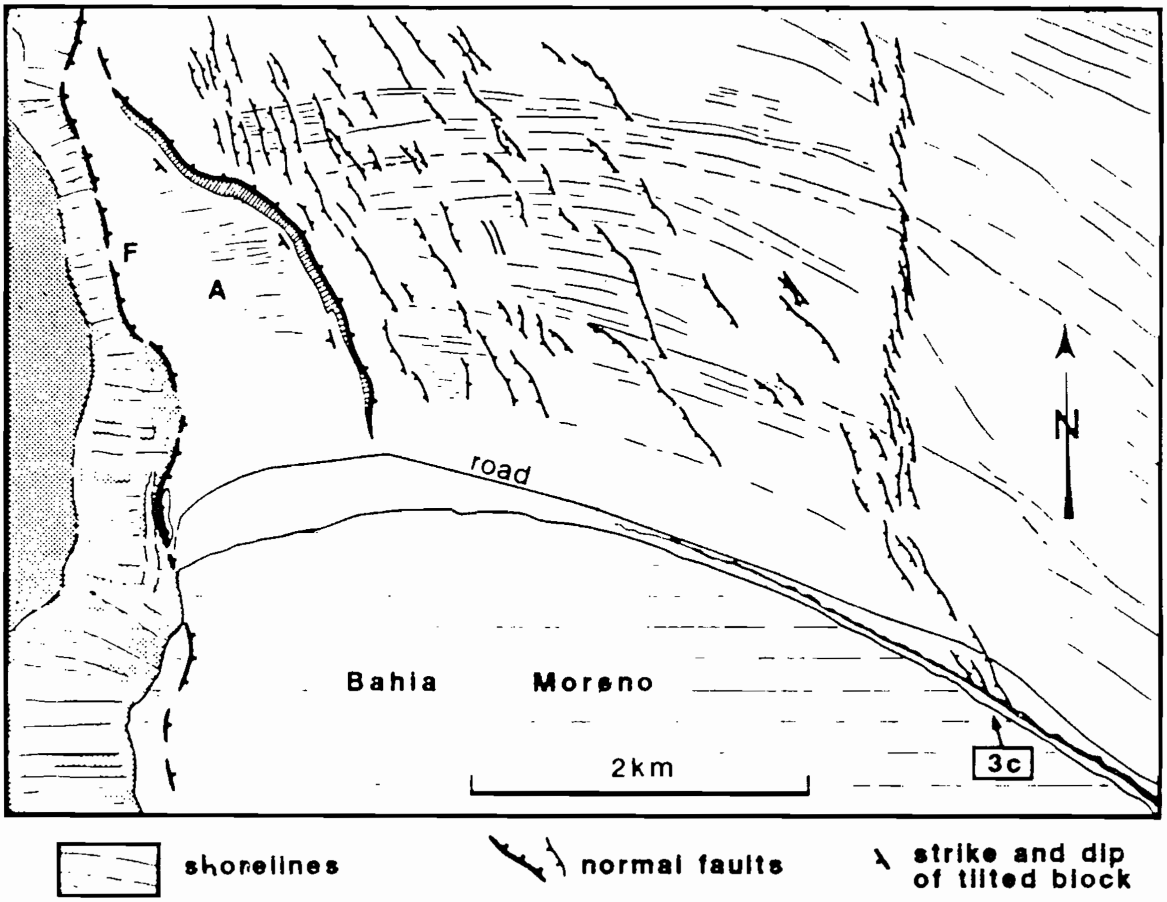


Fig. 1.2.4.- Late Quaternary faulting and block tilting in the nortwestern end of Antofagasta bay (from Armijo & Thiele, 1990). Locality « 3c » corresponds to Stop 1-2.

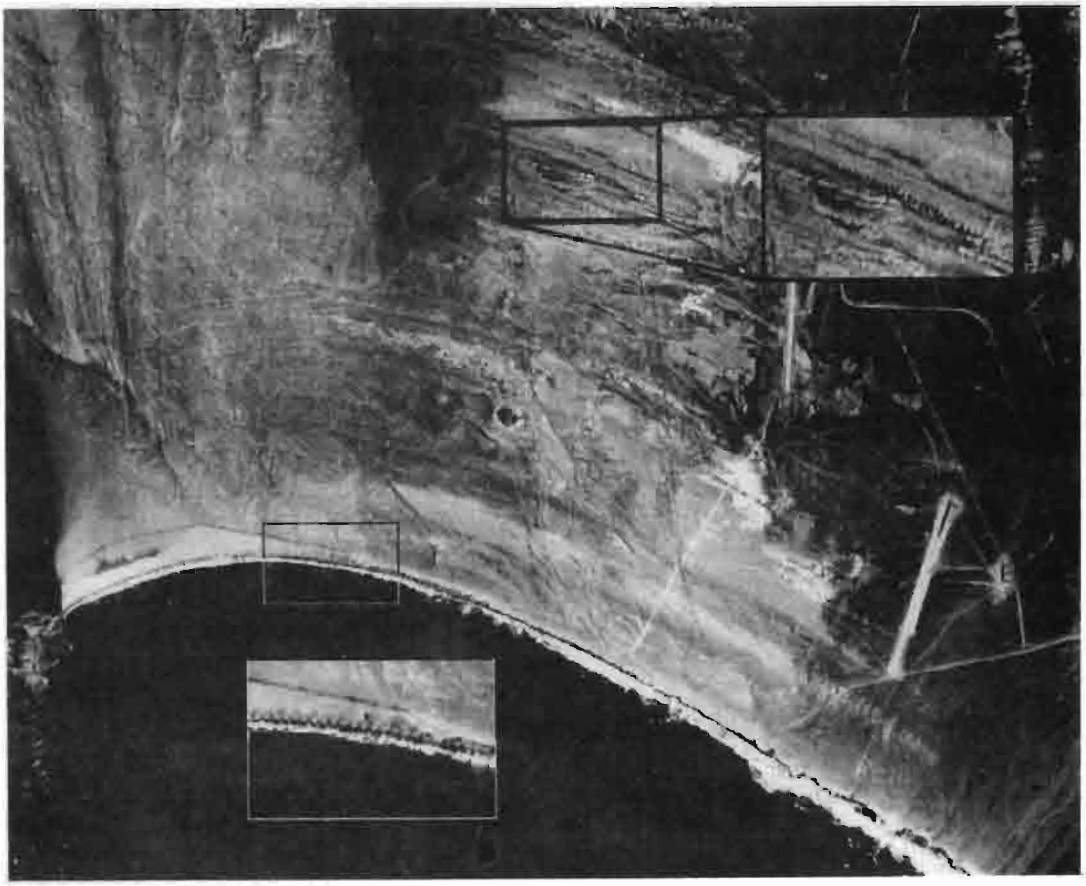


Fig. 1.2.5.- The exceptionally well preserved sequence of Middle Pleistocene beach-ridges in the southern Mejillones Peninsula. Note and compare the former beach cusps with those formed on the modern beach. Observe also, to the left, a southwestward-tilted faulted block (Document IGM, Hycoon 10089).

that, as seen in the previous stop, the marine terrace which is cut by the active seacliff is probably of IS 9 age (ca. 300 ka). On another hand Pliocene marine units, identified by their faunal remains, are commonly found at about +200 m, north of the beach-ridge sequence. A marine limit of Pleistocene transgressions is also clearly expressed in the relief (50+ m high palaeo-seacliffs) to the north, NE and E of the airport. Thus some elements tend to indicate that the lapse of timecovering the formation of the beach ridges may be of several hundred thousand years.

Though, it may be mentioned that, recently, Armijo & Thiele (1990) suggested that the whole sequences of beach ridges preserved, both north of Antofagasta bay and south of Mejillones bay were possibly of Late Pleistocene age (Fig. 1.2.6, terrace III). Actually, most of these coastal features were formed in the course of the Middle Pleistocene, and may encompass the whole Pleistocene period (Ortlieb, 1993). The chronostratigraphic assumptions of the former authors also led them, after others (like Okada, 1971), to interpret that some flat topped ridges like the conspicuous one of Cerro Bandurria (+400 m) (Fig. 1.2.6, Terrace I) were eroded during the early Pleistocene; nevertheless, Pliocene faunas related to the abrasion of the top of Cerro Bandurria clearly indicate that these marine abraded surface are older (Fig. 1.2.7).

These discrepancies in the chronostratigraphic interpretations have obvious implications on the determination of uplift rates. While Armijo & Thiele (1990) inferred uplift rates during the late Quaternary of the order of 2400 mm/10^3, we interpret that for the whole Quaternary period, the uplift of the Pampa del Aeropuerto, or Pampa Mejillones, was produced at a mean rate of the order of 100-200 mm/10^3 y.

LA RINCONADA: ASSIGNMENT TO THE ISOTOPIC STAGE 11 (ca. 400 ka) OF A WARM-WATER MOLLUSCAN ASSEMBLAGE

The tilted faulted block which lies north of La Rinconada is covered by a sequence of beach ridges in which a rich and unusual molluscan fauna was found (Fig. 1.2.8). The fauna includes many species which are proper to this outcrop (Fig. 1.2.9 & 1.2.10), and which are presently living at a much northern latitude (Peru and Ecuador).

By geometric consideration, it is inferred that the whole series of beach deposits which crop out on the tilted block are predating, by an interglacial cycle, the marine terrace of La Portada-Las Lozas. Thus the shorelines are interpreted as of IS 11 age.

In Table 1.2.1, a list of this faunal assemblage is compared to that of assemblages of other interglacial episodes in the bay of Antofagasta. Current studies (A. Díaz, L. Ortlieb, N. Guzmán) are aimed at determining if the « thermal anomalous molluscan assemblage » (« TAMA » of authors) is controlled by particularly favourable conditions in the locality of La Rinconada, and/or whether the IS 11 was, as suggested by some authors (Shackleton, 1986; Burckle, 1993), a warmer episode than any other of the Middle (and Late?) Pleistocene (Guzmán et al., 1995).

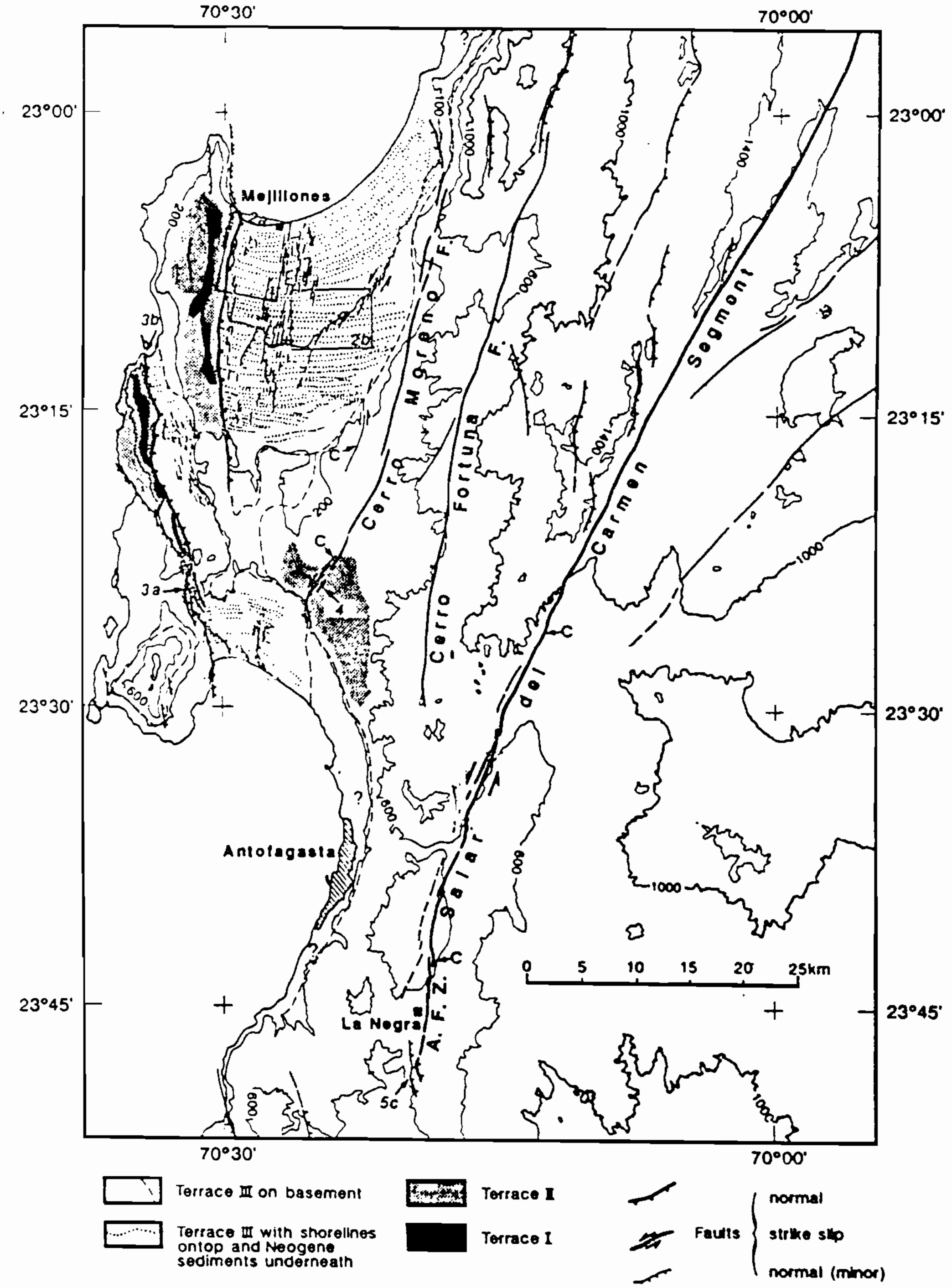


Fig. 1.2.6 - Sketch map of major neotectonic features of the Mejillones Peninsula and surrounding areas, according to Armijo & Thiele (1990). The authors distinguished three terraces (I, II, and III) of probable Pleistocene age. The terrace I with the sequences of beach ridges, interpreted by them as possibly of Late Pleistocene age, actually was formed in the course of the Middle (and Late?) Pleistocene.

Fig. 1.2.7.- Upper surface of Cerro Bandurria (SW Mejillones Peninsula), interpreted as a marine abrasion platform of possible Pleistocene age (Okada, 1971; Armijo & Thiele, 1990). Though, marine fauna preserved on this surface, at +400 m, points to a Pliocene age.

Fig. 1.2.8.- Expression of the major N-S trending fault that cuts the southwestern Mejillones Peninsula, immediately north of La Rinconada. This crustal fracture has been active during Middle and Late Quaternary. The marine sandstones in the foreground (at +10 m asl) are those which crop out upon the southwestward tilted La Rinconada tilted block.

Localidades :	Hol.	5e	7	9	11	>11
GASTROPODOS :						
Aeneator fontainei	X	P	P		P	P
Bulla punctulata	(X)				**P**	
Calyptraea (T.) trochiformis	X	M	A	M	M	M
Cancellaria (S.) buccinoides	X	P		P		P
Cerithium stercusmuscarum	--				**A**	
Collisella spp.	X	P	P	P		P
Concholepas concholepas	X	M	A	A	A	M
Crassilabrum crassilabrum	X	M	P	P	P	M
Crepidula spp.	X	A			P	P
Crepipatella dilatata	X	M	P	M	M	A
Crepipatella dorsata	X	M	P	M	M	M
Crucibulum quiriquinae	X	P	P	M	A	P
Diodora saturnalis	--				P	P
Fissurella costata	X	A	P	?		A
Fissurella crassa	X	P				A
Fissurella latimarginata	X	P	P			?
Fissurella maxima	X	P	P	P		P
Fissurella peruviana	X	P			P	p
Fissurella spp.	X	P	P	P	P	A
Liotia cancellata	X	?	?	?	**P**	?
Littorina (A.) peruviana	X	M				P
Mitra orientalis	X			P		A
Mitrella buccinoides	--				**P**	
Mitrella unifasciata	X					P
Nassarius dentifer	--	P				
Nassarius gayi	X	A	P	P	A	M
Nucella (A.) crassilabrum	?		P		P	P
Oliva (O.) peruviana	X	M	A	M	M	M
Olivella sp.	--				**M**	
Polinices (P.) uber	X		P	P	A	
Priene rude	X	M		P	P	P
Priene scabrum	X	A	P	P	M	A
Prisogaster niger	X	M	P	M	M	A
Prunum curtum	--				**A**	
Rissoina inca	X	?	P	?	P	P
Scurria spp.	X	A	P	P		P
Sinum cymba	X	?	P	P	P	
Siphonaria (T.) lessoni	X	P			P	P
Tegula (C.) atra	X	M	A	A		M
Tegula (C.) euryomphala	X	?	P	A	M	M
Tegula (C.) luctuosa	X	P	P		M	
Tegula (C.) tridentata	X	M	P	P	A	M
Thais (S.) chocolata	X	P		M	M	M
Thais haemastoma	X					
Trigonostoma tuberculosum	X		P			
Trimusculus peruvianus	X	P		P		
Turbo cf. T. fluctuosus	--				**A**	
Turritella cingulata	X	A	P	M	M	M
Xanthochorus buxea	X	P			P	P
Xanthochorus cassidiformis	X	P	P	A	P	P

Localidades :	Hol.	5e	7	9	11	>11
PELECIPODOS :						
Anomia peruviana	--				**A**	
Arcopsis solida	--				**P**	
Argopecten pupuratus	X	M	M	M	M	A
Aulacomya ater	X	P	P	P		P
Barbatia pusilla	X	P			P	P
Brachidontes granulata	X	P	P		P	P
Cardita sp.	--				**P**	
Carditella tegulata	X	P	A	P	A	P
Chama pellucida	X	M	P	P	A	M
Chione (L.) peruviana	--	P				
Choromytilus chorus	?	M	A	P	A	M
Cumingia mutica	?				**P**	
Cyclinella subquadrata	--			P		
Diplodonta inconspicua	X				P	?
Donax obesulus	(X)				**P**	
Ensis macha	X	P				
Eurhomalea lenticularis	?	A			P	
Eurhomalea rufa	X	M	P	A	A	P
Gari solida	X	P		P		P
Glycymeris ovatus	X	M	A	A	M	A
Mactra velata	--				**A**	
Mesodesma donacium	X	M	P	M	A	P
Mulinia cf. M. edulis	--	P	P	M	M	M
Mysella sp.	X	P			?	
Nucula cf. N. exigua	X		P			
Ostrea cf. O. columbiensis	–		M			
Ostrea megodon	--				**M**	
Perumytilus purpuratus	X	M	A			P
Petricola (P.) rugosa	X				A	
Protothaca (P.) thaca	X	M	M	P	A	A
Raeta (R.) undulata	--				?	P
Semele solida	X	P	P	M	M	P
Semele cf. S. corrugata	–			A	A	
Semimytilus algosus	X	P				P
Tagelus dombeii	X	A	P	P	A	P
Trachycardium cf. T. procerum	–				**M**	
Transennella pannosa	X	P	A	M	M	M
Venus antiqua	?	P			P	
Veneridae	--				P	

Table 1.2.1.- Comparison of the molluscan fauna in the bay of Antofagasta, between deposits coeval with the last major high sea stands correlated with the Late, Middle and Early (?) Pleistocene, and with the modern fauna of the area.

In bold are indicated the warmer-water species which are only found in the deposits tentatively assigned to the isotopic stage 11.

Fig. 1.2.9.- Middle Pleistocene nearshore deposit with « anomalously warm-water » fauna outcropping upon the tilted block, north of La Rinconada (Photo L.O.). See composition of faunal assemblage Table 1.2.1. The deposit is interpreted as of IS 11 age (ca. 400,000 y).

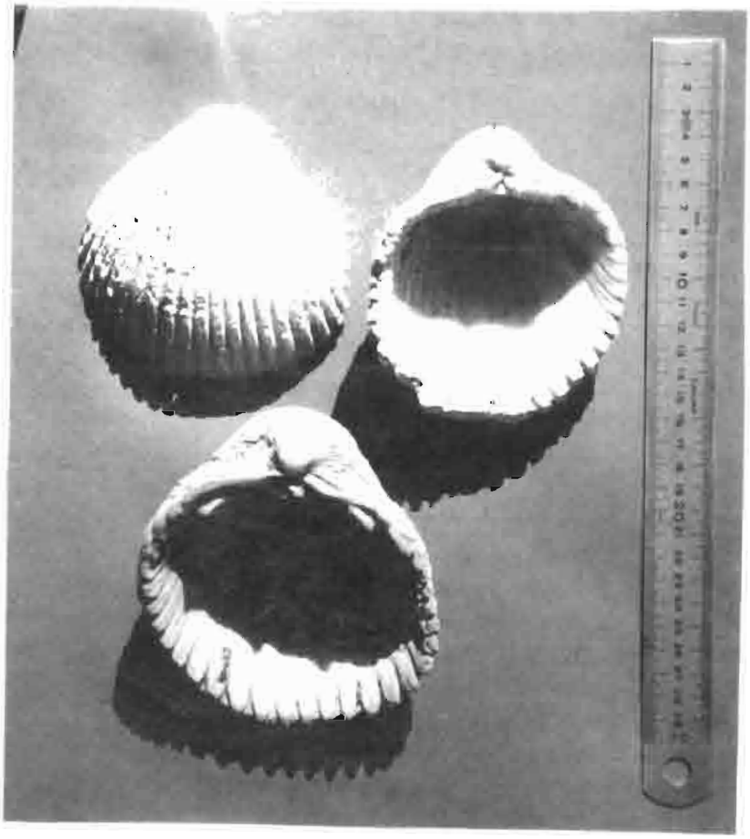


Fig.1.2.10.- Shells of *Trachycardium procerum,* a relatively warm-water species (presently living in northern Peru), only found in some marine terrace deposits in the peninsula of Mejillones. These fossils were sampled 3 km NNE of La Rinconada, atop the tilted block (Fig. 1.2.4).

At Stop 1-3 (Fig. 1.0.1), we shall observe a flight of staircased marine terraces and discuss their age. A few comments will also be made on the coastal uplift registered after the 1995 earthquake, through the measurement of a belt of dead crustose algae in the intertidal zone.

STAIRCASED FLIGHT OF MARINE TERRACES IN THE SOUTHWESTERN MEJILLONES PENINSULA

Around the bay of Juan López and in several areas of the southwestern extremity of the Mejillones Peninsula, were preserved series of marine abraded platforms. The terraces were cut at varying elevations up to about +150 m asl. Near Juan López, the oldest terraces are hidden by the alluvial fan deposits accumulated at the foot of Cerro Moreno. The most complete sequence of abraded platforms of Pleistocene age is found to the east of Caleta Constitución, on the western side of the Mejillones peninsula (Fig. 1.3.1), but unfortunately, they are generally devoid of any marine deposit.

Previous work in the area was peformed by Radtke (1989) and Ratusny & Radtke (1988) (Fig. 1.3.2 & 1.3.3). North of the village of Juan López, four conspicuous marine terraces are distinguished. Elevation of the inner edge of the staircased terraces are about +20 m, +35 m, +60 m and >+90 m. The wave-cut platforms are covered with nearshore sediments including conglomerates and sandstones, with variable amount of faunal remains.

ESR and U/Th analyses on mollusks from the three major terraces (Radtke, 1989) did not provide precise results (Fig.1.3.4).

Unexpectedly, the lower and younger marine terrace, which is preserved almost all around the Abtao embayment and is partly covered with late Quaternary alluvium (Fig. 1.3.5), did not yield geochronological results that suggest a correlation with the last interglacial. U-series (both by α spectrometric method and TIMS) and amino-acid racemisation analyses yielded data that would suggest an assignment to the IS 7 interglacial (Table.1.3.1). Nevertheless these geochronological results should be taken with more prudence than usual.

A particularity of the faunal composition of the deposit associated with the lower terrace at Abtao is its richness in a species of oysters (*Ostrea* cf. *O. columbiensis*). This particularity cannot be interpreted in terms of chronology of the unit.

If one accepts the assumption that the lower terrace at Abtao-Juan López was formed during the IS 7, this would imply that the remains of the last interglacial should be preserved at or below present sea level. Relatively small but well-preserved remnants of a wave cut platform can be seen in the eastern part of Abtao embayment (Fig. 1.3.6): they were possibly cut during the IS 5 (5e?).

CO-SEISMIC COASTAL UPLIFT DURING THE 1995 EARTHQUAKE

The southwestern corner of Mejillones Peninsula registered the highest uplift motion of the coastal area associated with the 1995 earthquake (Fig. 1.3.6). The measurement of the sudden co-seismic uplift was performed through a monitoring of a white belt that appeared in the intertidal zone in rocky areas (Ortlieb et al., 1995). The belt resulted from

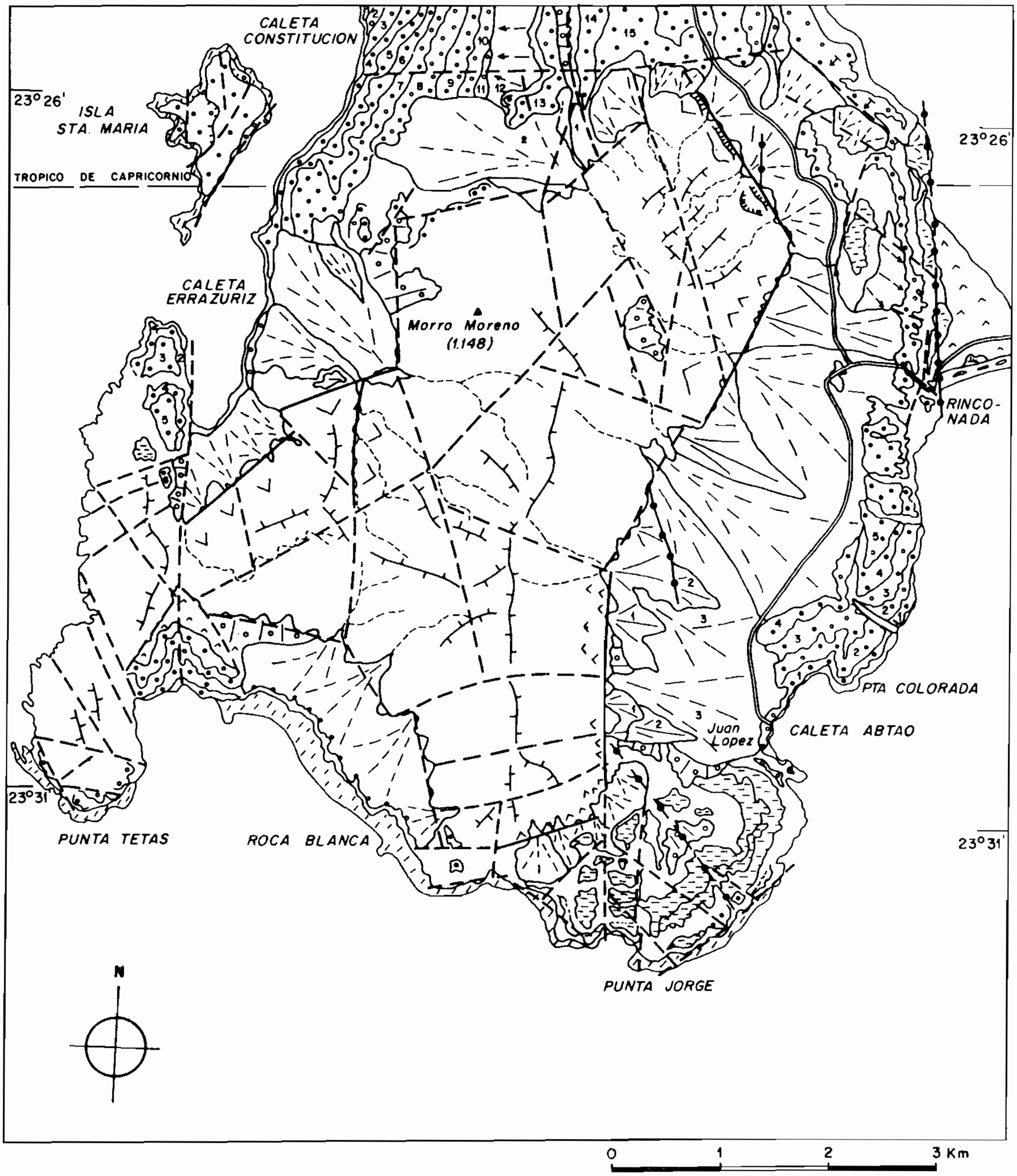


Fig. 1.3.1.- Geological sketchmap of the southwestern extremity of Mejillones Peninsula, with special emphasis on the sequences of marine terraces and wave-cut platforms (see legend of Fig. 0.1.6).

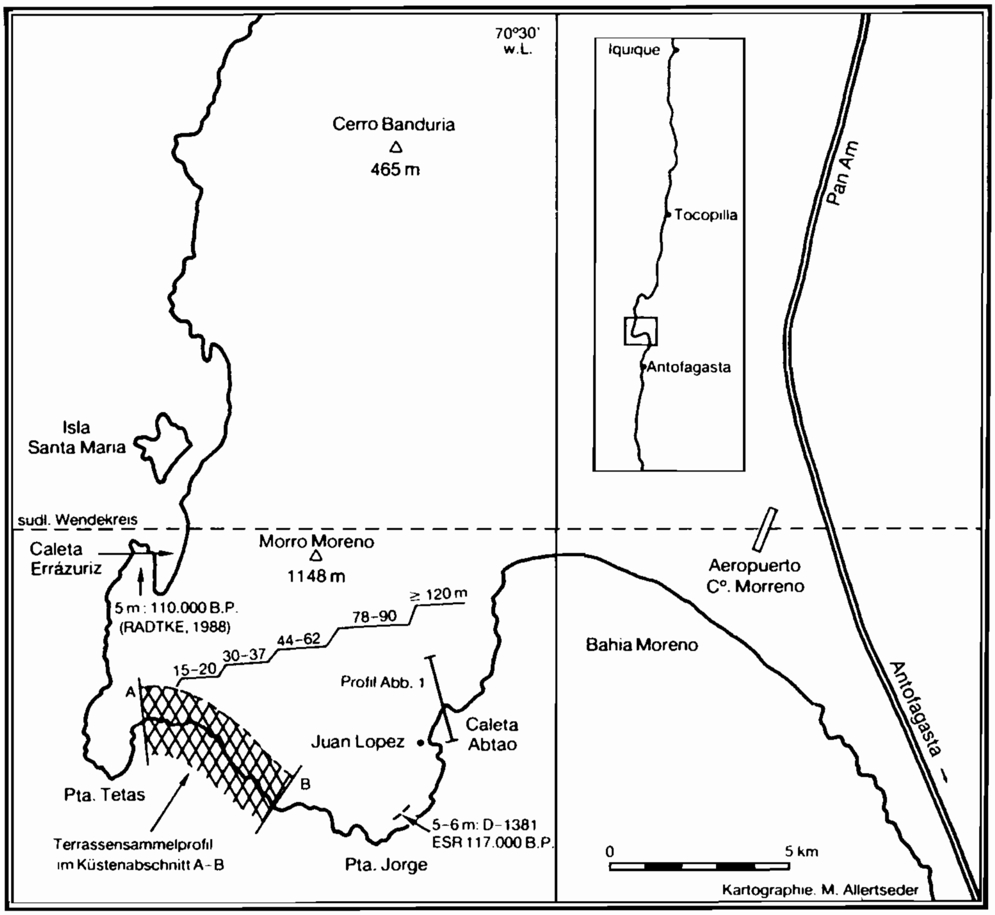


Fig. 1.3.2 .- Sequence of staircased marine terraces recognized by Ratusny & Radtke (1988) in the southwestern extremity of Mejillones Peninsula.

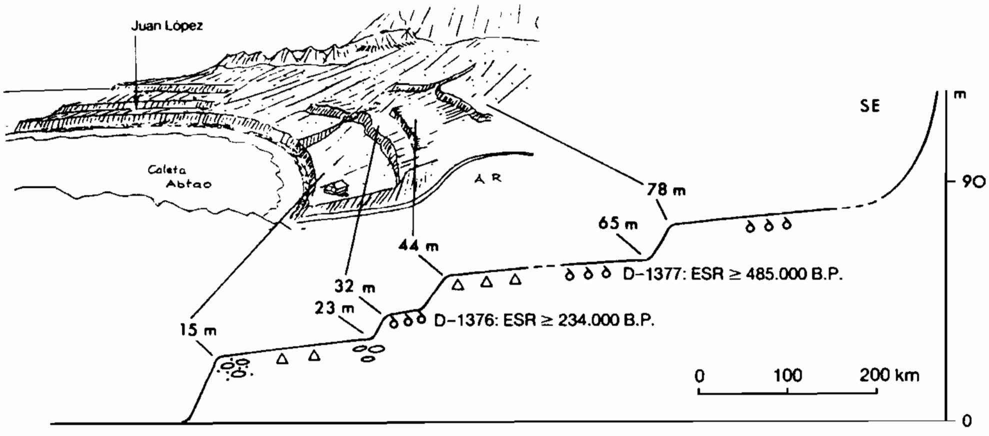


Fig. 1.3.3.- Staircased marine terraces on the northwestern coast of Abtao bay (Juan López) (from Ratusny & Radtke, 1988).

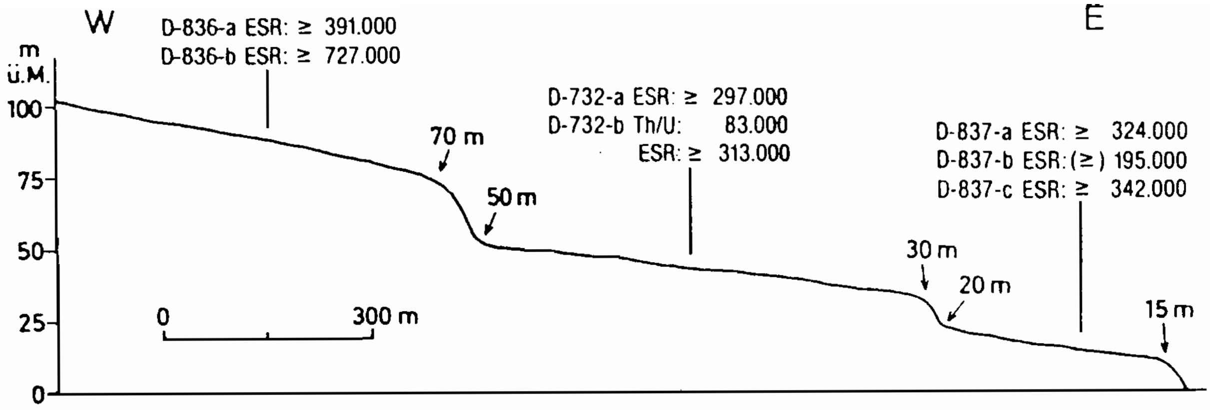


Fig. 1.3.4.- Geochronological results (ESR and U/Th dating) on fossil shells from the three major terraces bay of Abtao, obtained by Radtke (1989).

Sample	Elevation (m asl)	Species	A/I	s	n	U/Th (a)	U/Th (TIMS)	Interpretation
C93-42	8	*P. thaca*	0.64	0.04	2	223 ±29		IS 7
			-	-		237 ±11		IS 7
			-	-			231 ±8	IS 7
C92-35	80	*P. thaca*	0.73	0.12	2			IS 9
C92-27	80	*P. thaca*	0.73	0.04	2			IS 9

Table 1.3.1.- Geochronological results obtained on marine terraces in the area of Juan López (unpublished data from GEOTOP).

Fig. 1.3.5.- Seacliff NW of Juan López, showing a marine abrasion surface (+ 8m) covered by nearshore fossiliferous sediments (1 m thick, in white) and by several metre thick alluvium. Marine fossils suggest an older than IS 5e age, and may be assigned to the IS 7.) (Photo L.O.).

Fig. 1.3.6.- Wave-cut platform to the north of the small peninsula of Abtao, which was probably formed during a high stand of the last interglacial (IS 5c ?). The white belt at 30 cm above water line is the dead lithothamnium fringe that appeared in august 1995 (see Fig. 1.3.7.-). (Photo L.O.).

the death of the upper part of lithothamnium crust which commonly covers the substratum and boulders in the subtidal and lowermost intertidal zone. It provided a precise measurement of the area which was suddenly dessicated as a consequence of the uplift.

Fig. 1.3.6, taken at the northeastern end of the embayment of Caleta Abtao, in September 1995, shows a example of this white belt (which will probably have disappeared when the excursion party visits the locality!). At Abtao, the belt measured 25 cm, while at La Rinconada it was less than 5 cm, and at Punta Jorge (S of Abtao) it measured 31 cm (Fig. 1.3.7). Highest uplift measured in this way was observed on the western side of Mejillones Peninsula (Fig. 1.3.8).

A combination of the data obtained in the intertidal zone and GPS measurements performed along an E-W oriented network that covers the area between the Pacific Ocean and the foot of the Andes Cordillera, should provide a reasonable estimate of the vertical co-seismic deformation (Ruegg et al., 1995, in prep.).

Fig. 1.3.7.- White fringe of dead lithothamnium which provides a precise evaluation of the coseismic uplift registered along the coast on July 30, 1995 (Ortlieb et al., 1995). The photo was taken at Punta Jorge, 2,5 km SSW of Juan López. (Photo L.O.).

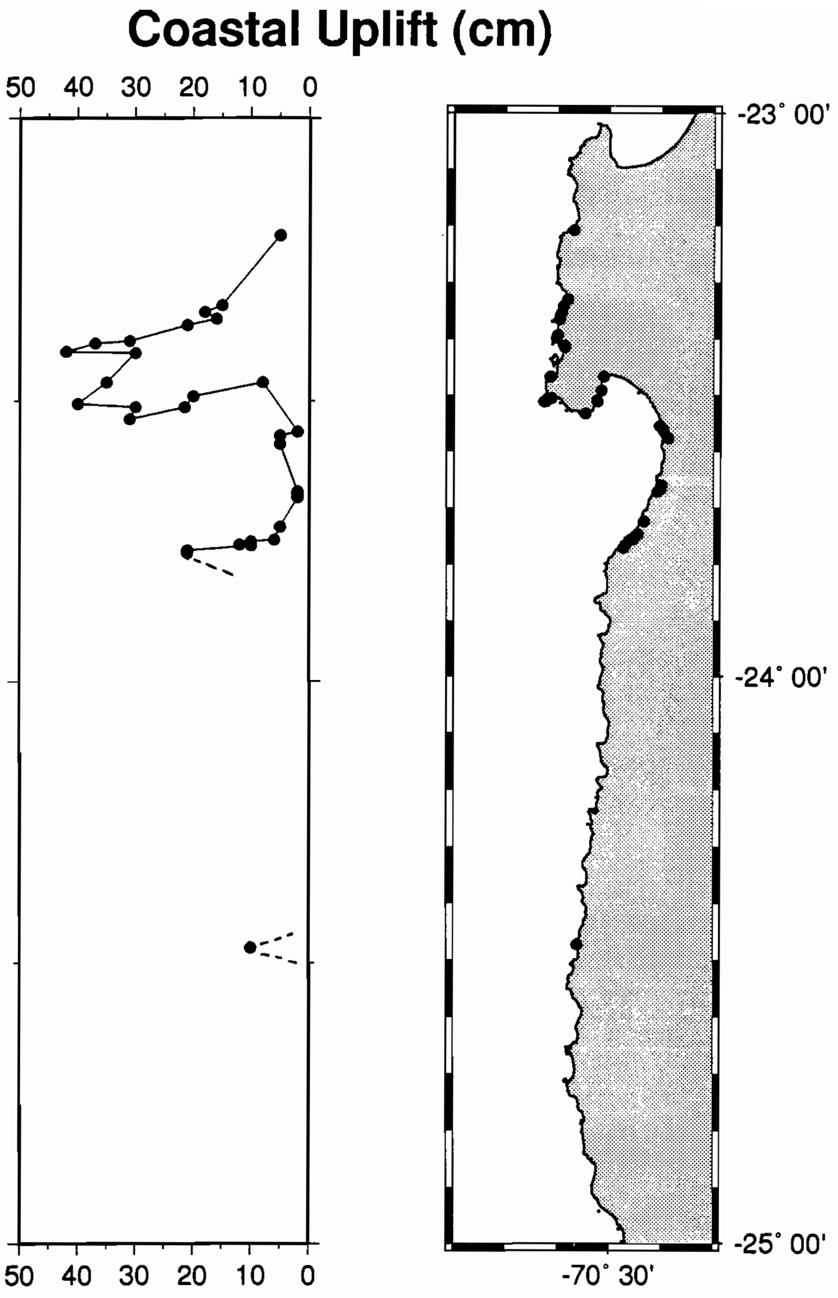


Fig. 1.3.8.- Diagram of the coastal uplift measured after the 1995 earthquake in the southern Mejillones Peninsula and the Antofagasta bay, by using the width of the dead lithotamnium belt as indicator (from Ortlieb et al., 1995).

VARIATIONS IN ENVIRONMENTAL AND OCEANOGRAPHIC CONDITIONS FROM ARCHAEOLOGICAL SEQUENCES

At Stop 1-4, we shall comment the potential of archaeological sites for paleoceanographic and paleoenvironmental changes in an arid coastal area.

The site of Abtao-1: possible oceanographic change in the mid-Holocene

The cultural sequence of the Abtao-1 site includes three phases of occupation (Llagostera et al.,1994) (Fig. 1.4.1). The oldest one, Abtao I shows many features common with the « First Preceramic Period » of Bird (1943-46). It was dated 5350 BP and is characterized by the co-occurrence of shell and cactus thorn hooks (Fig. 1.4.2) During the second occupation phase (Abtao II), another type of hook (straight stemmed hooks), made of bone, appears in the impedimenta. In the last phase which begins at ca. 3500 BP the hooks display a retaining head.

During the first occupation phase, it was observed by Llagostera (1979a) that the relative abundance of some shell and fish species varied throughout the stratigraphic sequence of the shell mounds. Namely the number of *Choromytilus chorus*, a mussel shell adapted to cool waters was decreasing upward, while the relative abundance of remnants of the fish *Trachurus murphyi*, which is more common during warm water episodes, was increasing (Fig. 1.4.3). It was disclosed that this double evolution was not due to human over-exploitation, and thus, that it suggested a relative warming-up of the coastal waters in the period 5350-4000 BP.

Quebrada Las Conchas: a warm episode at the beginning of the Holocene ?

Opposite the bay of San Jorge, is one of the oldest archaeological sites of the northern coast of Chile. The site of Quebrada Las Conchas provided to Llagostera (1979) two radiocarbon ages of 9400 and 9680 BP. The Qda. Las Conchas site is closely related to the Huentelauquén Culture, characterized by geometric stones (Fig. 1.4.4).

In the Qda Las Conchas site, otoliths of fishes that are now living in Ecuadorian waters have been found (Llagostera, 1979a, 1979b). It was thus inferred that around 9,500 BP, the water in San Jorge Bay was warm enough to permit fishes, like *Cynoscion analis* and *Micropogon altipinnis*, to survive in the area (4,000 km more to the south than at present). But it could not be determined yet whether these warmer water conditions were permanent, or episodical (El Niño-like conditions, of short duration). Another aspect of the problem is that the otoliths are found together with mollusk shells which do not suggest that the nearshore conditions were significantly different from the present ones. In the framework of a FONDECYT Project, we shall try to get paleotemperature data (from isotopic analyses on shells and otoliths) and thus compare paleoceanographic information between organisms living permanently in the coastal area of Antofagasta, and fishes which are susceptible to move along the coast (according to the temperature, for instance).

The site of Qda Las Conchas is located 3 km inland (from the present shoreline), on top of a dune that was built at the foot of the Coastal Scarp. As this dune is half-closing a *quebrada,* far from any known *aguada,* it has been inferred that some water was probably

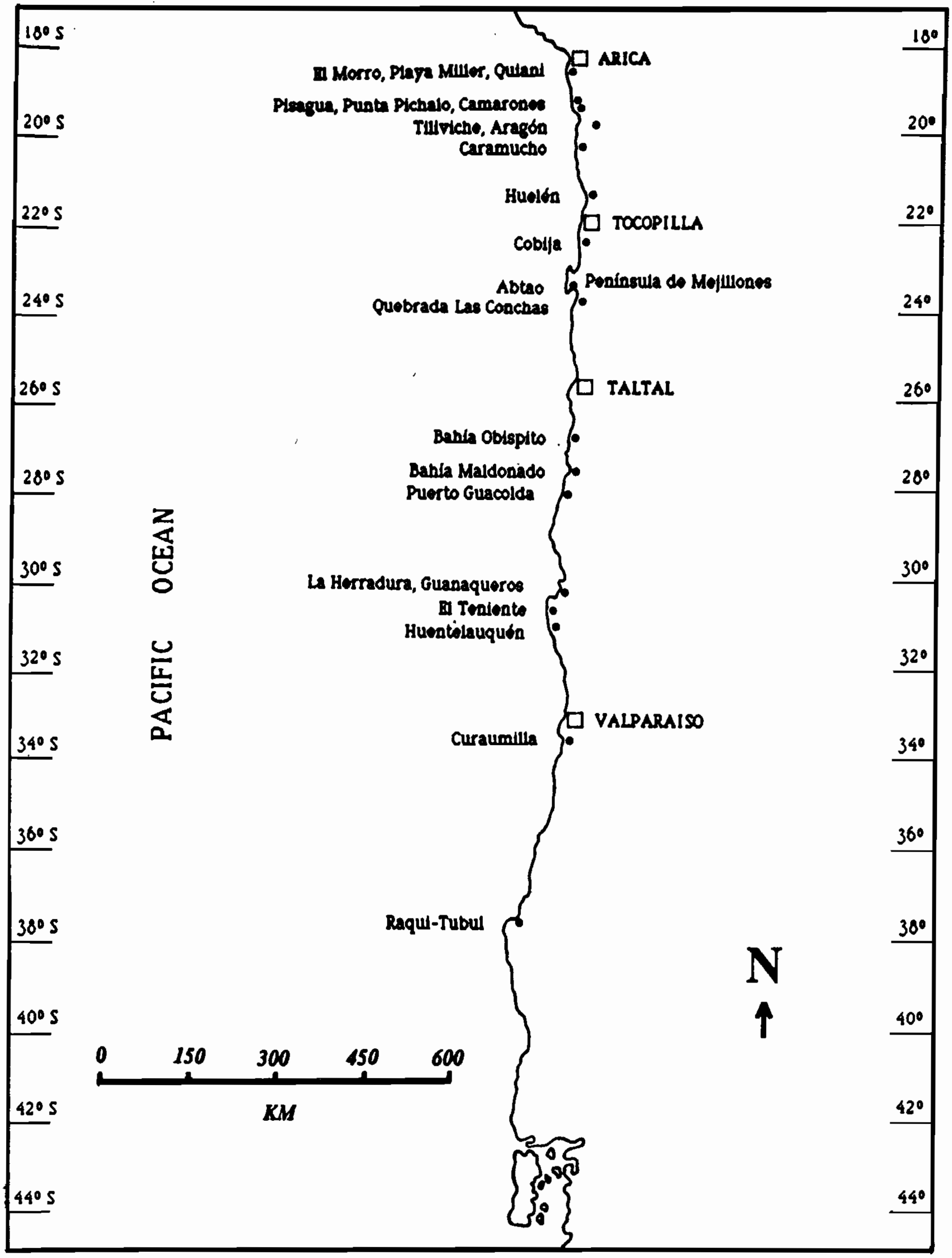


Fig.1.4.1.- Major archaeological sites along the coast of northern Chile (from LLagostera, 1992).

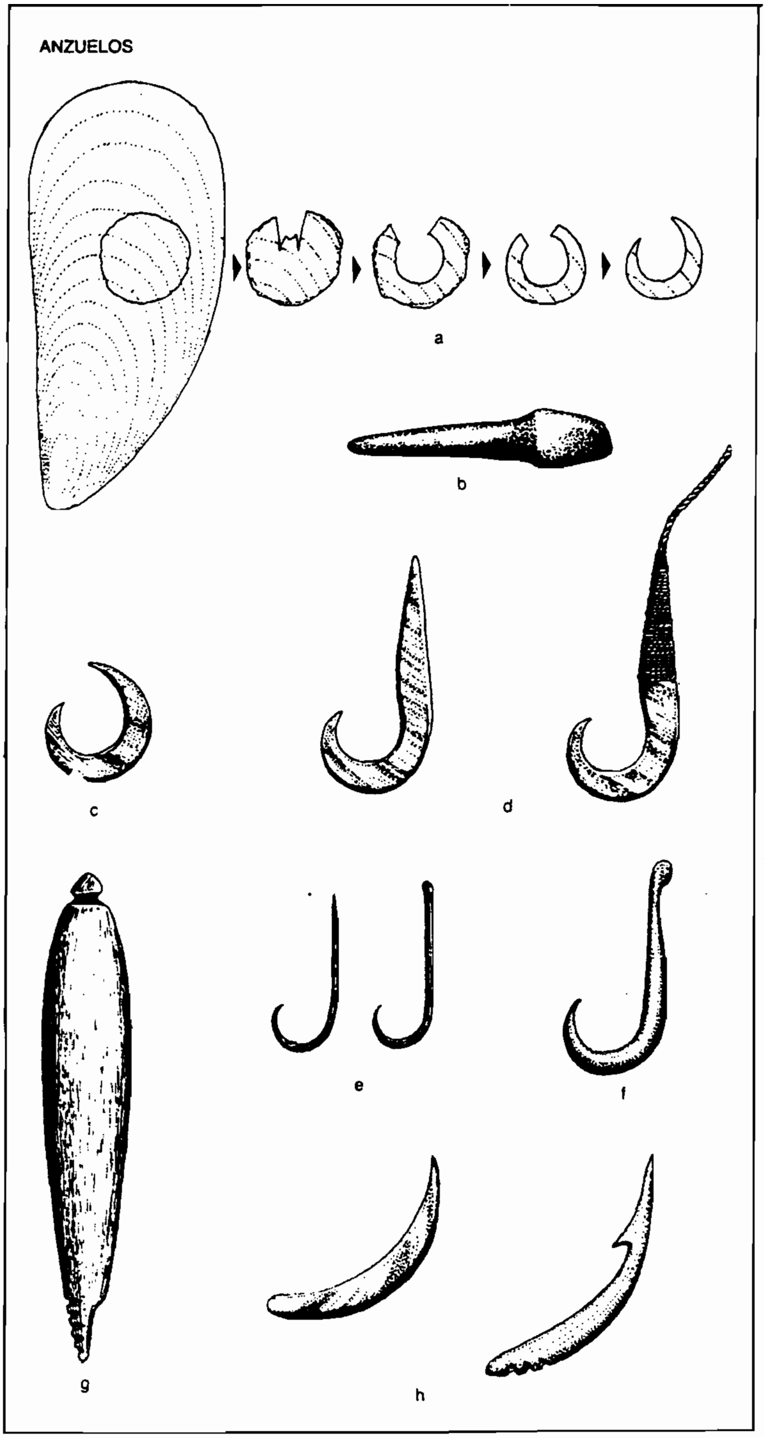


Fig.1.4.2.- Fishooks (made of mollusc shell, cactus thorn or bone) found in archeological sites of northern Chile (from Llagostera, 1989).

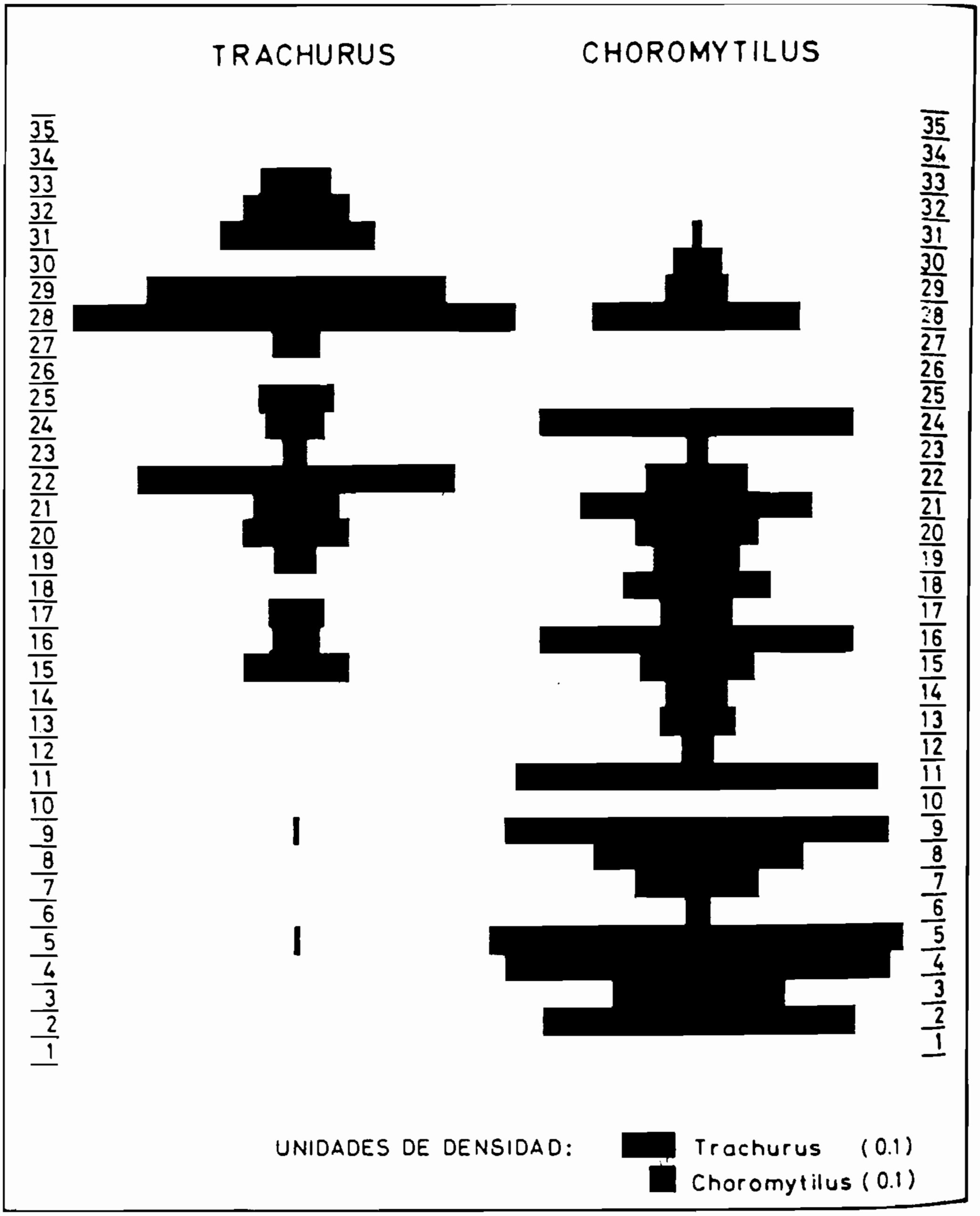


Fig.1.4.3.- Inverse relative abundance of *Choromytilus chorus* (mussel) and *Trachurus murphyi* (warm-water fish) in the lower part of the stratigraphic sequence of site Abtao-1 (from Llagostera, 1979a). The bio-indicators suggest a warming episode in the bay of Antofagasta between 5350 and 4000 BP.

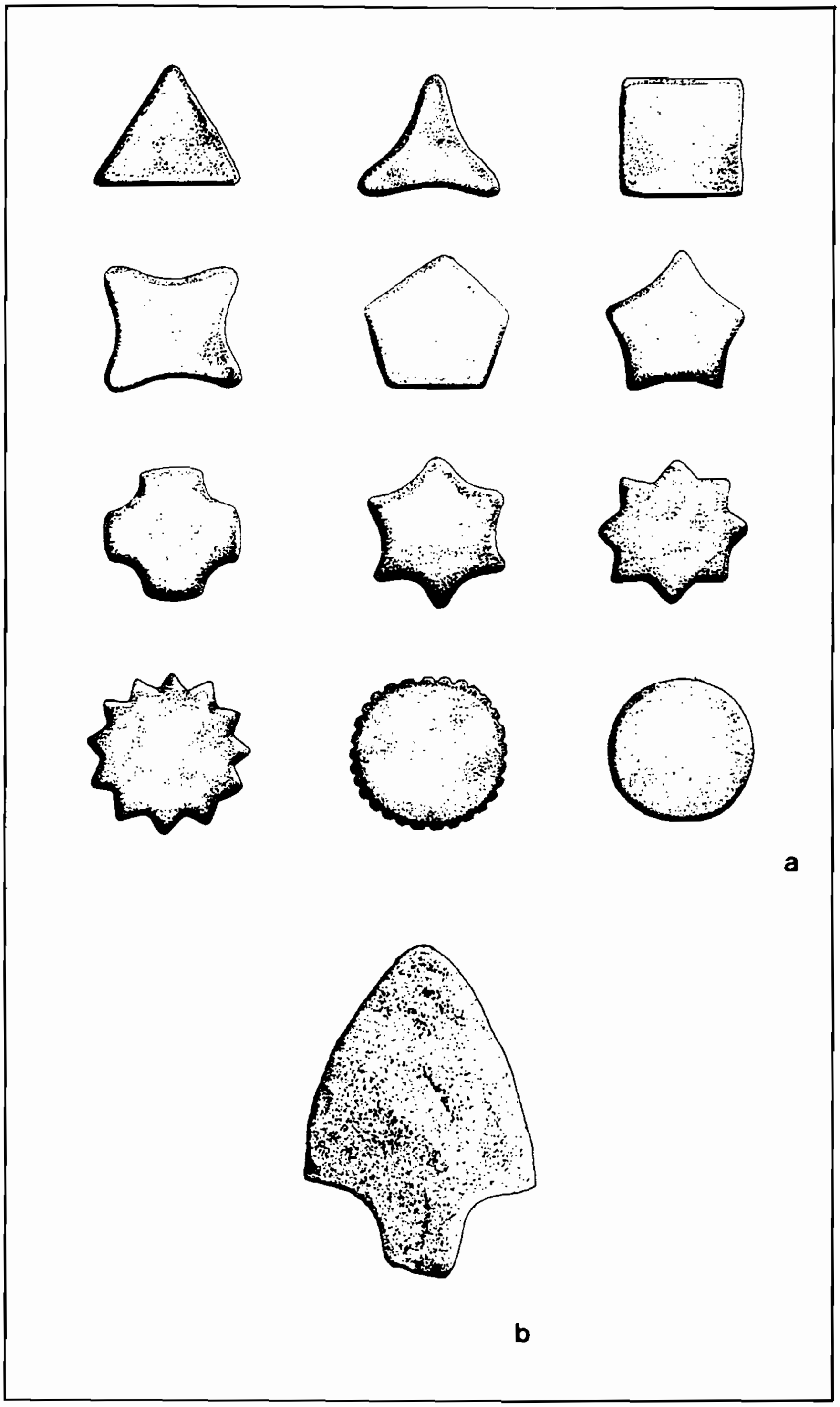


Fig. 1.4.4.- Geometric stones typical of the Huentelauquén Culture (ca. 9500 BP), similar to those collected in the Quebrada Las Conchas (Antofagasta) site (from Llagostera, 1989).

flowing, at least episodically, in the presently dry river bed. The hypothesis of warmer seawater conditions would support a slightly more humid climate at the time of human occupation (Llagostera, 1979a, 1979b). On another hand, it can be noted that the site could have been a ceremonial centre (which would explain the abundance of geometric stones), in which case it would not have been necessarily well provided with running or standing water.

At Stop 1-5, we will comment the chronostratigraphic interpretation of a wide series of beach ridges which document the uplift of the Pampa Mejillones during the Quaternary.

THE EXTENSIVE BEACH-RIDGE SERIES OF PAMPA MEJILLONES

The beach ridge sequence

The northern part of the isthmus of Mejillones Peninsula is formed, like the southern part, by a large plain slowly dipping toward the sea (Mejillones Bay). The plain called Pampa Mejillones is about 20 km long from N to S, and about the same size from W to E. It is limited to the west by a large, complex, fault scarp (see next Stop), and to the east by the foot of the Cordillera de la Costa. At its highest point, Pampa Mejillones reaches an elevation of +220 m. To the north it ends on the edge of a 10/20 m high seacliff.

The plain is totally covered with beach ridges sub-parallel to the present coastline. This series of former regressive shorelines has an unusual extension; much larger than its counterpart on the southern side of the Mejillones Peninsula. The ridges, which are easily seen on aerial photographs and satellite images (Fig. 1.5.1 & 1.5.2.) are even better preserved than more to the south. They are generally less cemented than those of Pampa Aeropuerto and kept their original shape (Fig. 1.5.3) . They are commonly 1 to 2 m high and are separated from one another by swales of varying width (50 to 200 m). They consist of shelly sands mixed with an important proportion of well rounded pebbles. In some places, the morphological ridges are replaced by linear outcrops of marine sands which may be very fossiliferous (Fig. 1.5.4). The faunal content of the ridges and associated marine deposits varies across the series. Some of the most elevated deposits (cropping out at an elevation above +150 m, due south of Mejillones) contain a molluscan fauna wich includes warm-water elements, particularly *Trachycardium procerum*. A chronological correlation between this set of beach ridges with the warm-water unit previously mentioned at La Rinconada is thus attempted. It would suggest that the ca. +160 m deposits are assignable to the IS 11.

The chronostratigraphic interpretations

The chronostratigraphy of the series of beach ridges has not yet been established. Several interpretations were proposed. One of the earliest ones was that of Herm (1969) who noted a major discontinuity in the geometry of the series of beach ridges and who considered that it corresponded to a transgressive maximum (Fig. 1.5.5 & 1.5.6). On the basis of the Quaternary chronological scale established in the area of La Serena-Coquimbo, Herm interpreted that the discontinuity marked the limit between the Serena II and Serena I deposits (Early and Middle Pleistocene).

According to another interpretation (Okada, 1971; Armijo & Thiele, 1990), already mentioned above (Stop 1-2), the whole series of beach ridges would have been formed during the regression subsequent to the last high sea stand, i.e. the last interglacial. As discussed by Ortlieb (1993), this interpretation was based on an assumption and did not take into account previous paleontological and geochronological data.

Fig. 1.5.1.- The exceptional series of emerged Pleistocene beach ridges in Pampa Mejillones, which extends 20 km from N (Mejillones) to S, between elevations of 0 to +210 m. Location of Fig. 1.5.2 & 1.5.5 are indicated.

Fig. 1.5.2.- Series of Pleistocene beach ridges in southern Pampa Mejillones, between elevation of +150 and +200 m (N is to the left). Occurrence of warm-water fauna in these deposits suggests an IS 11 age. (Document Serv. Aero Fotogramétrico, 80 CH60-S.4, n° 008526).

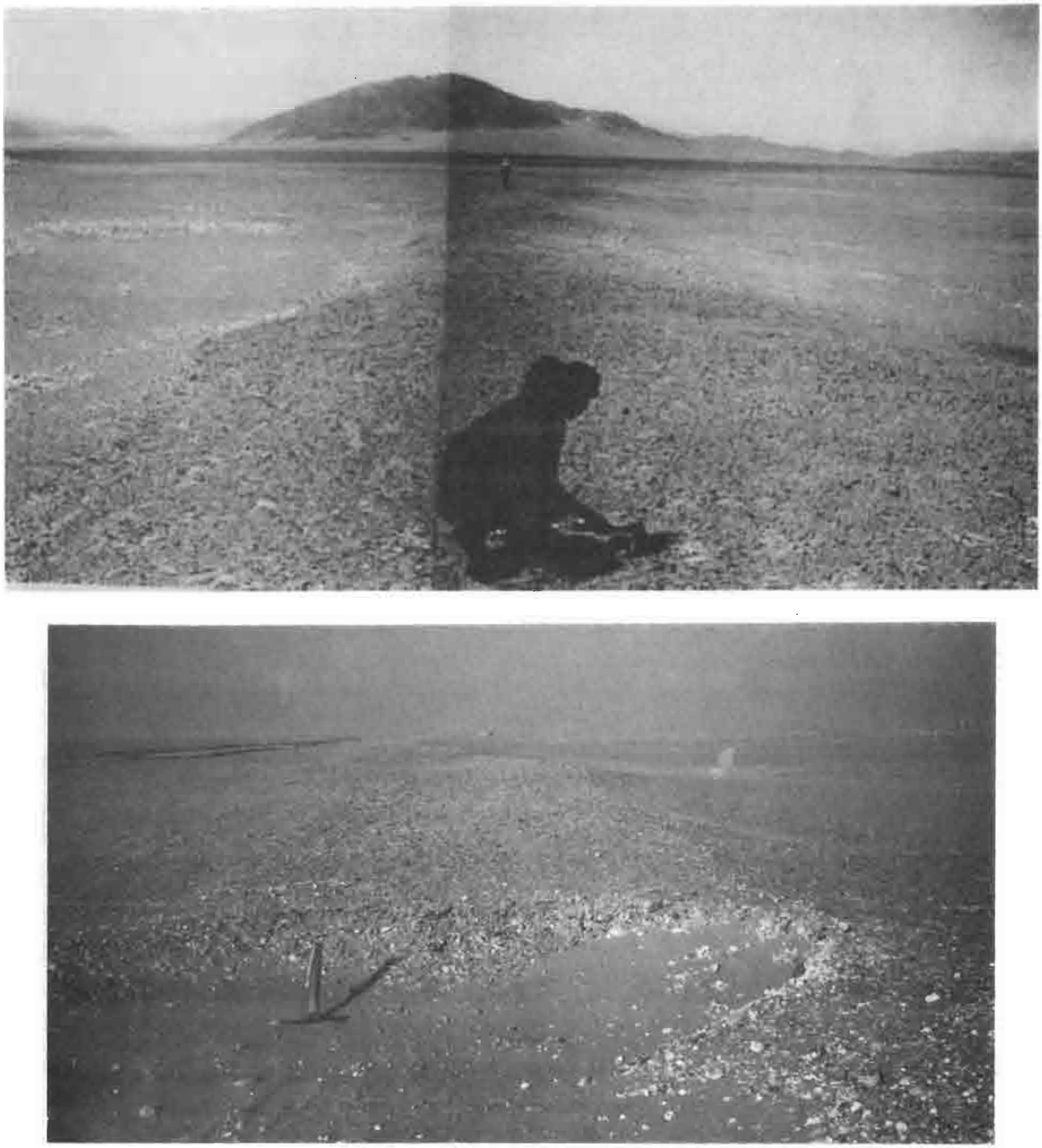


Fig. 1.5.3.- Well preserved Pleistocene beach ridges of Pampa Mejillones. Above: at a +200 m elevation, in the southern part of the pampa; below: at a +60 m elevation (Photos L.O.).

Fig. 1.5.4.- Fossiliferous nearshore sediments outcropping on Pampa Mejillones. Above: warm-water fauna (with *in situ Trachycardium procerum* shells) at a +160 m elevation; below: sub-tidal accumulation of normally cool-water species (+100 m elevation). (Photos L.O.).

Fig. 1.5.5.- Lower (northern) part of Pampa Mejillones with the youngest series of Pleistocene beach ridges. Arrows indicate the trace of a transgessive limit separating two sets of beach ridges (see Fig. 1.6. . & 1.6.). (Document Serv. Aero Fotogramétrico, 80 CH60-S.4, n° 008528).

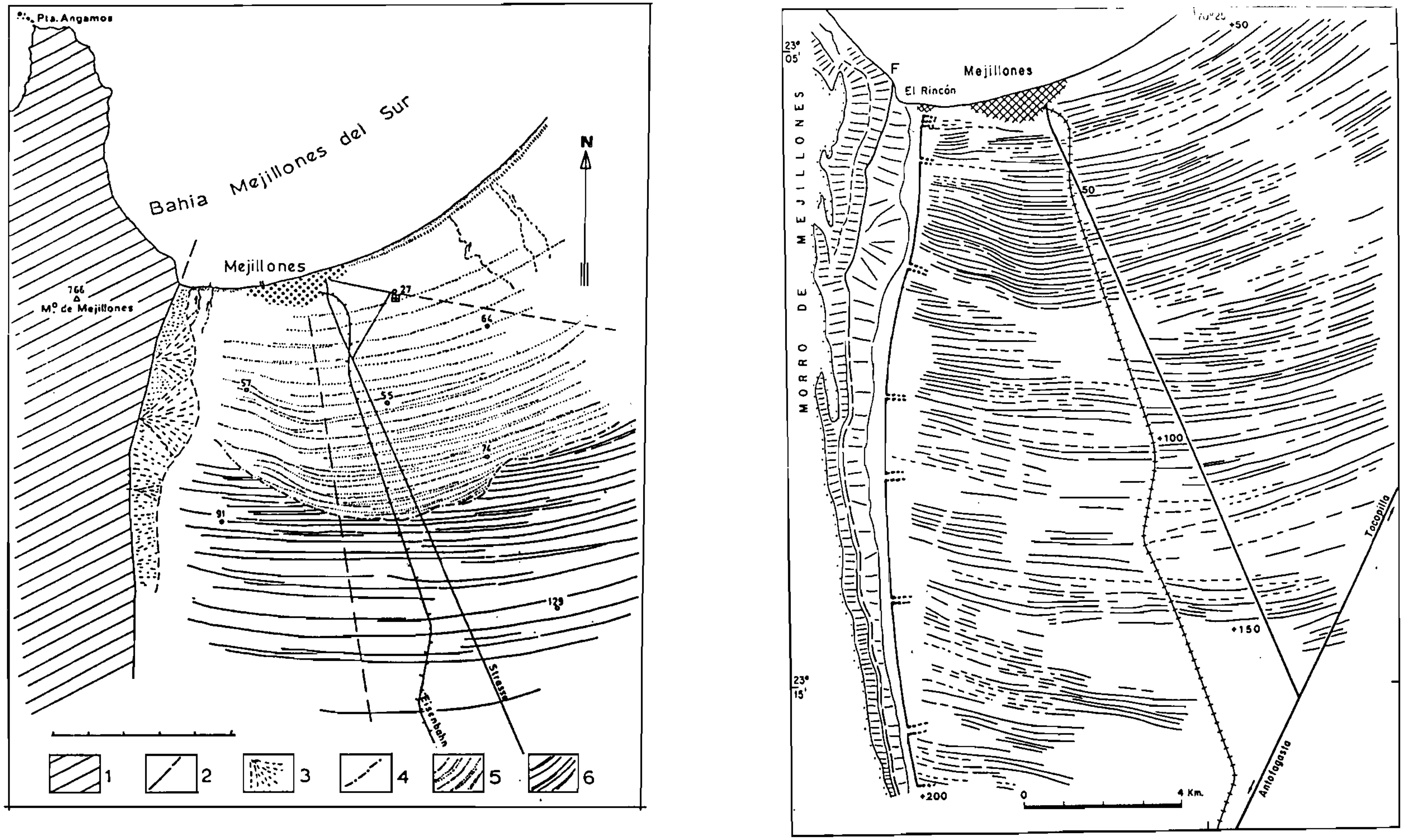


Abb. 6: Auflagerung der Sedimente der Serena-II-Ingression auf Strandwällen einer älteren Ingression, südlich Mejillones; (Auswertung der Luftbilder HYCON Nr. 10093, 10094):
1 = Grundgebirgszug, horstartig gehoben; 2 = West-Randstörung der Grabenscholle; 3 = Schuttkegel; 4 = Südgrenze der Serena-II-Transgression, leicht erodiert; 5 = Strandlinien und -wälle der jüngeren Serena-II-Regression; 6 = Strandwälle der Regression eines älteren (Serena-I) Meeresvorstoßes. 1 Teilstrich des Maßstabes entspricht 1 km.

Fig. 1.5.6.- Two previous interpretations of the chronostratigraphy of the younger beach-ridges of Pampa Mejillones:

Left: according to Herm (1969) the shorelines of the lower series would belong to the Serena II unit, and the older series (above +80 m) to the Serena I unit.

Right: taking into account available ESR and U/th dating results (Radtke, 1989) at El Rincón, Ortlieb (1993) intented to distinguish a series of cycles, that would correlate with Middle (and Early?) Pleistocene interglacials.

Craig (1988) had proposed a still shorter chronology for the beach-ridge series: based on a few radiocarbon dates obtained on shells collected at +150 m, he believed that the whole sequence could have been formed in less than 30,000 y. The finite radiocarbon results must have resulted from a contamination by modern carbon.

Finally we may recall (see Stop 1) that according to the geological map (Ferraris & Di Biase, 1978, Fig. 1.0.1), the northern half of the beach-ridge sequence would be Pleistocene while the southern half is assigned to the Pliocene La Portada Fm. There is no doubt whatsoever that Pliocene beds constitute the bedrock of a marine abrasion in the Pampa Mejillones, and that the beach ridges (together with associated fossiliferous coastal deposits which crop out at the surface) are of Pleistocene age. Nevertheless, some authors (see for instance Fig. 1.6.1) still relie on the disputable stratigraphic definition of the Mejillones Fm.

In 1993, Ortlieb proposed to divide the sequence of beach ridges in a series of cycles which would represent successive interglacial highstands of the sea. This hypothesis was based on the few previously available geochronological results from Radtke (1989) and on an interpretation of the discontinuities observed between sets of beach ridges (as analysed on aerial photographs). In 1995, a new interpretation, which takes into account the faunal composition of the deposits found between +150 and +200 m and a correlation with the La Rinconada warm-water fauna, will be submitted to the participants (see Fig. 1.5.8).

Geochronological results

Since 1985, Radtke (1985, 1987a, 1987b, 1989) published geochronological results obtained on shells sampled in three staircased coastal deposits that crop out at El Rincón, in the NW extremity of Pampa Mejillones (Fig. 1.5.7). These terraces necessarily postdate the last-formed beach ridges of the Pampa Mejillones sequence. The ESR and U/Th results tend to indicate that the three terraces were formed coevally with the last three interglacials.

Numerous U-series and aminostratigraphic analyses were performed recently on shells collected at varied elevations in the sequence and in the same deposits of staircased terraces that were sampled by Radtke. The high $^{234}U/^{238}Th$ ratios (>1.2) indicate that the U is not of marine origin. The late diagenetic uptake of U explains that surprisingly young apparent ^{230}Th ages were obtained in some localities.

The aminoacid data indicated in Table 1.5.1 concern a series of samples between the edge of the seacliff and an elevation of +160 m. The relatively spread results probably reflect differences in the thermal history of the samples, from one locality to the other. Though, in general terms the results show increasing ratios with the elevation of the localities. The major problem of interpretation remains the lateral correlation with other localities and the age assignment to the localities. It must be noted, for instance, that the warm-water fauna deposit that is tentatively correlated with the IS 11, yields Allo/Isoleucine ratios of the order of 0.9, which are higher than in other localities supposedly of IS 11 age.

Thus the chronostratigraphic interpretation, and subsequently the neotectonic recent history, of Pampa Mejillones requires some more work. The paleontological approach may finally be promising, but it remains to establish in close-by and remote localities that the IS.11 was effectively warmer than any other interglacial episode.

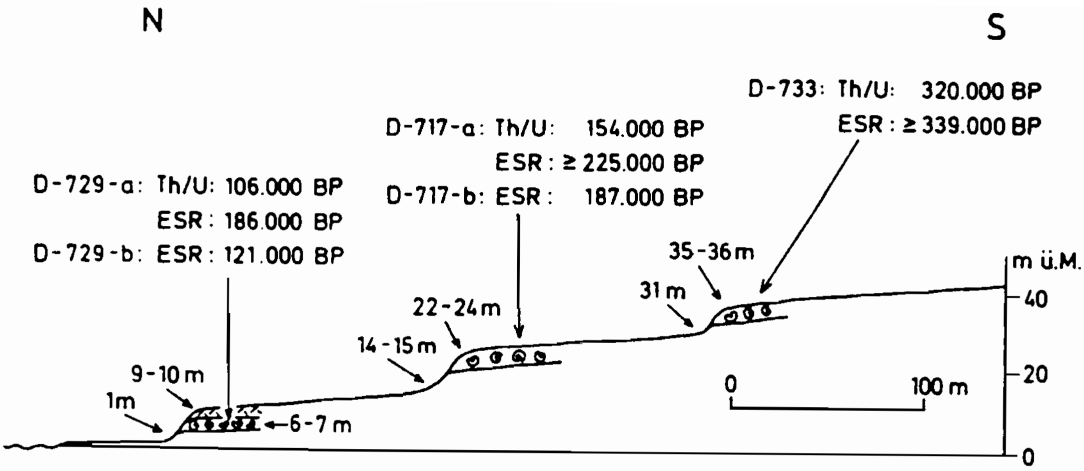


Fig. 1.5.7 .- Geochronological results (ESR and U/Th dating) on fossil shells from the three lower staircased terraces at El Rincón, obtained by Radtke (1989).

Sample	Elevation	Species	A/I	n	sigma	interpr.
C92-36	+ 25 m	*M. edulis*	0,49	2	0,05	5e
C92-36	+ 25 m	*V. antiqua*	0,41	1		5c?
C94-126	+ 70 m	*M. edulis*	0,55	3	0,03	7?
C93-46	+ 110 m	*P. thaca*	0,83	3	0,04	?
C94-125	+ 110 m	*M. edulis*	0,78	3	0,08	?
C89-5	+ 120 m	*P. thaca*	0,78	2	0,06	?
C94-124	+ 130 m	*M. edulis*	0,85	2	0,11	?
C94-117	+ 160 m	*P. thaca*	0,92	2	0,08	11
C94-117	+ 160 m	*V. antiqua*	0,85	2	0,10	11?

Table 1.5.1.- Aminostratigraphic data on marine shells from beach ridges of Pampa Mejillones (unpublished results of GEOTOP).

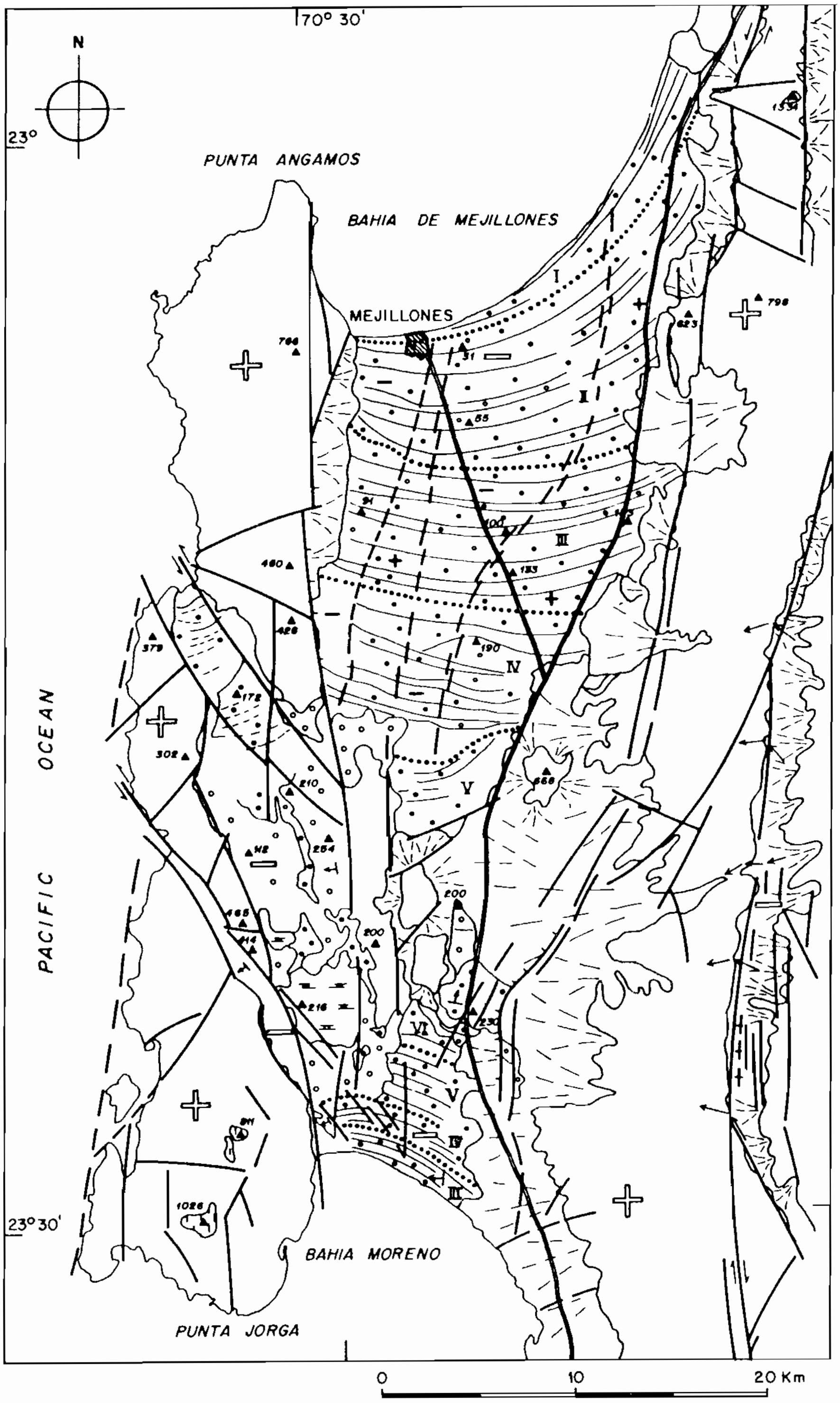


Fig. 1.5.8.- General tectonic sketch map of Mejillones Peninsula, with the last interpretation of the chronostratigraphy of the beach-ridge series of Pampa Mejillones, based on a correlation of the warm-water fauna of cycle IV (+150/+160 m elevation) with IS 11 (ca. 400 ka) (Ortlieb, Goy, Zazo, in prep.).

The last Stop of the first day will permit to observe a scarp of the Mejillones Fault cutting Late Quaternary alluvial fans. We shall also discuss there some other aspects of the tectonic activity in the northern half of the Mejillones Peninsula.

THE MEJILLONES FAULT

The Mejillones Fault forms the boundary between Pampa Mejillones and the range of Morro Mejillones (Fig. 1.6.1). It is a major crustal fault which has been active for most of the Cenozoic times. The last activity of this fault is evidenced by a scarp which is about four metres high (Fig. 1.6.2). The age of this last deformation is not well constrained, but may be pre-Holocene in spite of the apparent freshness of the feature.

Mejillones Fault acts as a boundary for the semi-graben of Pampa Mejillones, but this semi-graben is itself uprising, as evidenced by the preservation of the beach-ridge sequence. No chronostratigraphic correlation of Pleistocene marine units across the fault zone have been established. Nevertheless an evaluation of minimum net offset during the Quaternary may be proposed. The highest elevated outcrop of Pleistocene sediments lies at a +440 m elevation on the uplifted block, west of the fault (Fig. 1.6.3). As the highest elevated Pleistocene deposits identified in Pampa Mejillones, east of the fault, are cropping out at about +220 m, a minimum vertical offset of 220 m is inferred for the last 1 My (or 1,6 My).

OTHER FAULTING ACTIVITY IN NORTHERN MEJILLONES PENINSULA

Another fault which may be compared with the Mejillones Fault, is the one which limits to the west the small, NNW-SSE oriented, graben of Caleta Herradura de Mejillones (Fig. 1.6.4). The Caleta Herradura de Mejillones Fault had an activity similar to that of the Mejillones Fault. It also offsets by at least 200 m Pliocene and Pleistocene marine terraces.

The Pampa Mejillones is cut by a complex system of relatively recent faults which generally trend N-S. Some of the faults, particularly on the western side of the pampa, near the trace of Mejillones Fault, display several metre (up to 25 m) high scarps (Fig. 1.6.5). Other faults have practically no superficial expression, as those visible in the present seacliff at Mejillones (Fig. 1.6.6). The latter are normal faults which had some activity during the sedimentation of the coastal units, at least locally.

Thus the Pampa Mejillones semi-graben has been an active tectonic area for most of Quaternary times. In a sense it is surprising that being cut by numerous N-S oriented faults, and en échelon fault systems, the pampa recorded so well the parallel beach ridges formed in the course of the last several hundred thousand years.

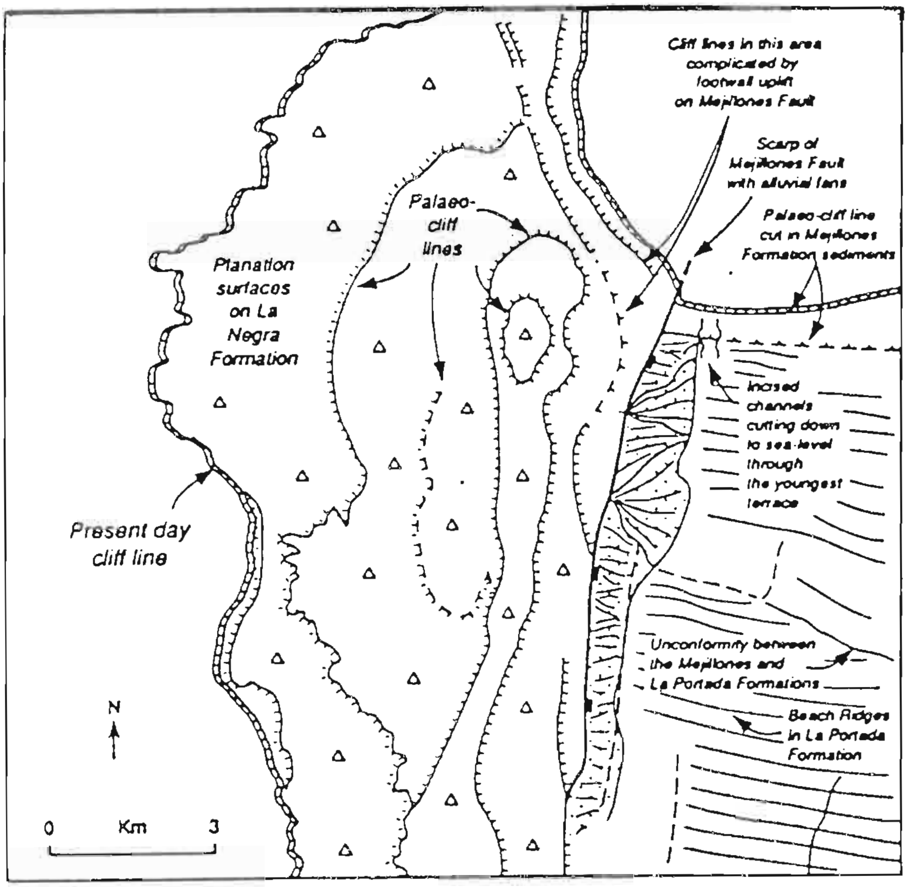


Fig. 1.6.1.- Sketch map of the Morro Mejillones area, showing the Mejillones Fault scarp (from Hartley & Jolley, 1995). It can be noted in the lower right corner that the authors assigned part of the beach ridge series of Pampa Mejillones to the Pliocene La Portada Fm.

Fig. 1.6.2.- Mejillones Fault scarp that cuts a Middle Quaternary alluvial fan, at the foot of the uplifted Punta Angamos-Morro Mejillones fault block. The several metre high scarp is well preserved (because of the aridity), but seems to be pre-Holocene (Photo L.O.).

Fig. 1.6.3.- Highest elevated marine deposit with Pleistocene fauna, due west of the town of Mejillones, at +440 m asl. View looking to the south (Photo L.O.).

Fig. 1.6.4 .- Aspects of the strong late Cenozoic tectonic activity in Caleta Herradura de Mejillones, northwestern Mejillones Peninsula:

- in the foreground, Late (or late Middle?) Pleistocene marine terrace (ca. +50 m elevation), with a thin layer of marine sediments;
- in the distance, to the right: seacliff showing folded and faulted Pliocene beds overlying a Miocene marine sequence (see Fig. 1.1.4),
- and in the background, two wide marine abraded platforms (at +250 and +400 m elevations). The highest marine platform of Cerro Jorgino is presumably of Pliocene age, like that of Cerro Bandurria (Fig. 1.2.7). (Photo L.O.).

Fig. 1.6.5.- Late (?) Quaternary faulting of Pampa Mejillones: 10-20 m high, N-S trending, fault scarps cutting the Middle Pleistocene marine deposits. In the foreground, sandstone ridges that underline small fault lines associated to the fracture system (hammer for scale).(Photo L.O.).

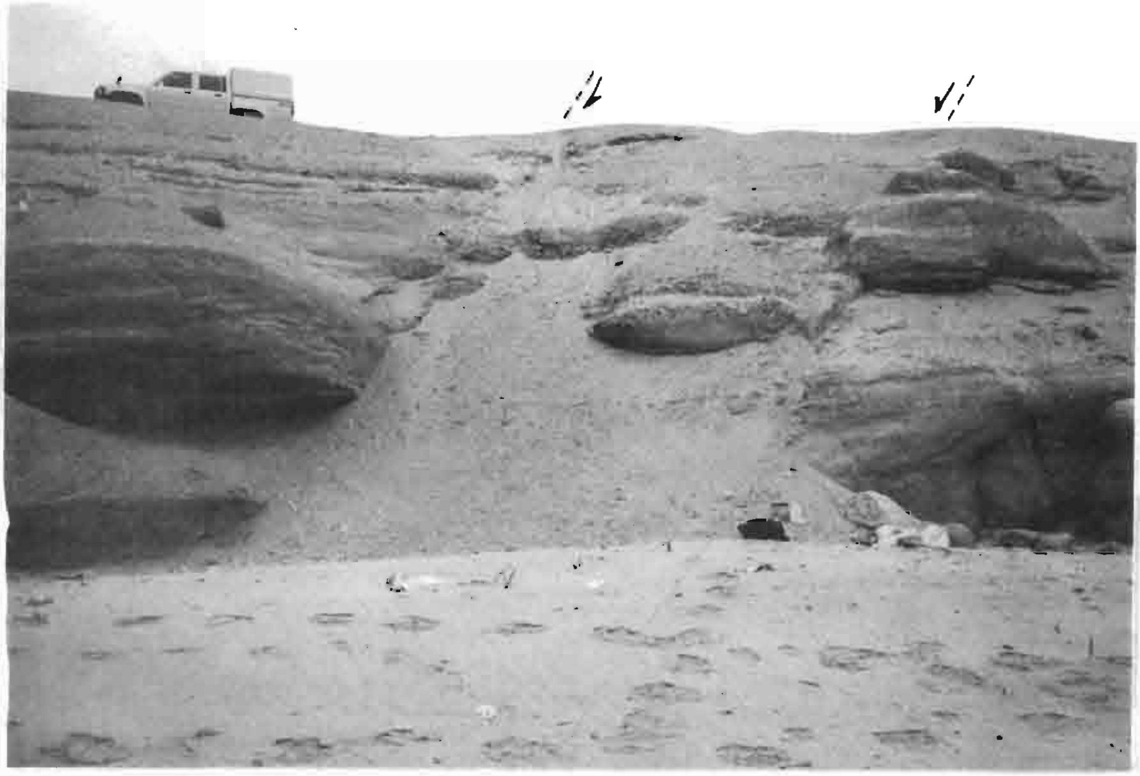


Fig. 1.6.6.- Normal fault system cutting the Middle and Late Pleistocene coastal units that crop out in the seacliff east of Mejillones. The extensional faults trend N50°E and display vertical offset of up to 4 metres. (Photo L.O.).

LATE QUATERNARY COASTAL CHANGES IN NORTHERN CHILE

Guidebook for a fieldtrip
(Antofagasta-Iquique, 23-25 november 1995)

organized during the 1995 Annual meeting of the
International Geological Correlation Program Project 367
(19-28 November, Antofagasta, Chile)

Second day of Fieldtrip

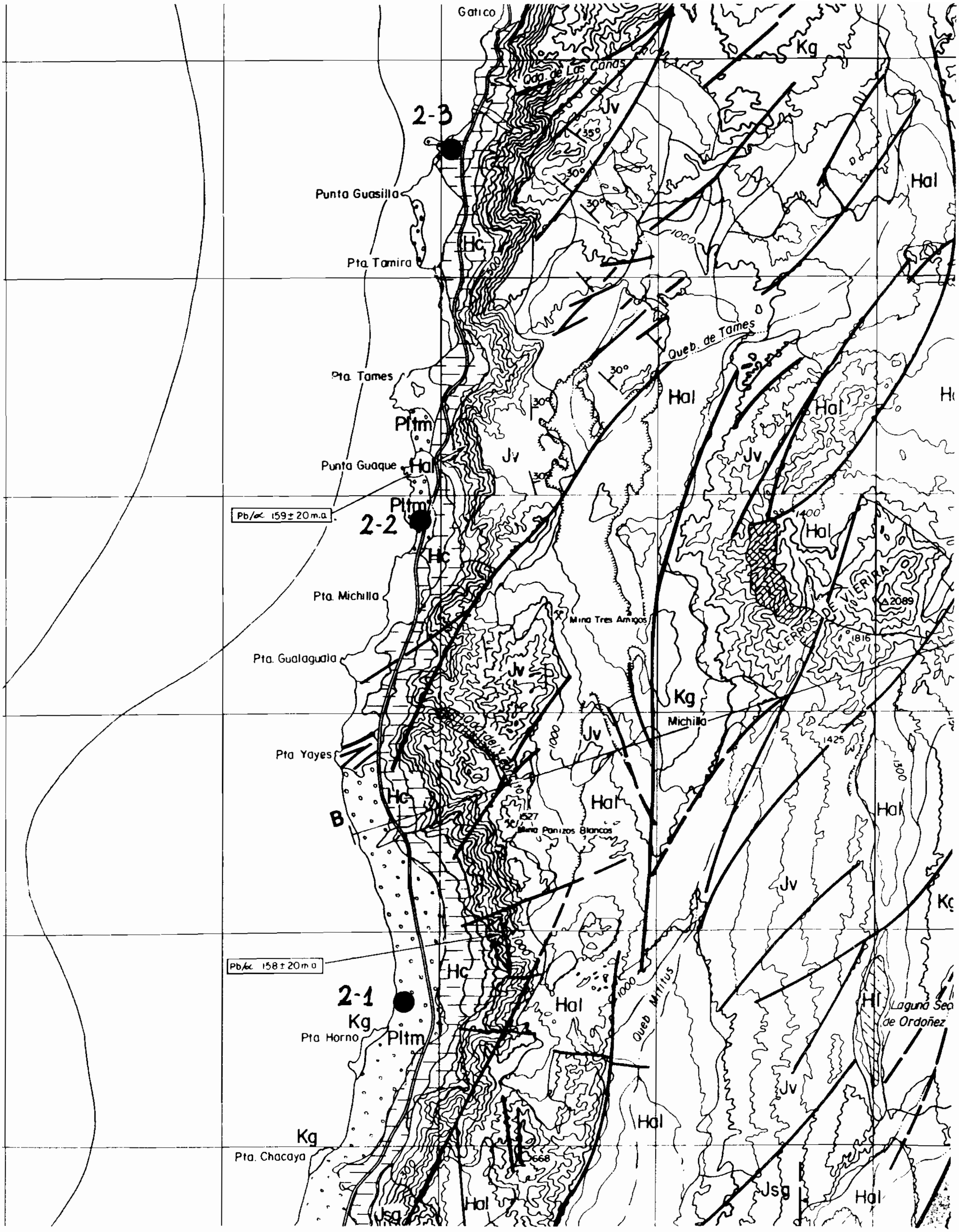


Fig. 2.0.1.- Localisation of the first stops of the second day, between Hornitos and Gatico.

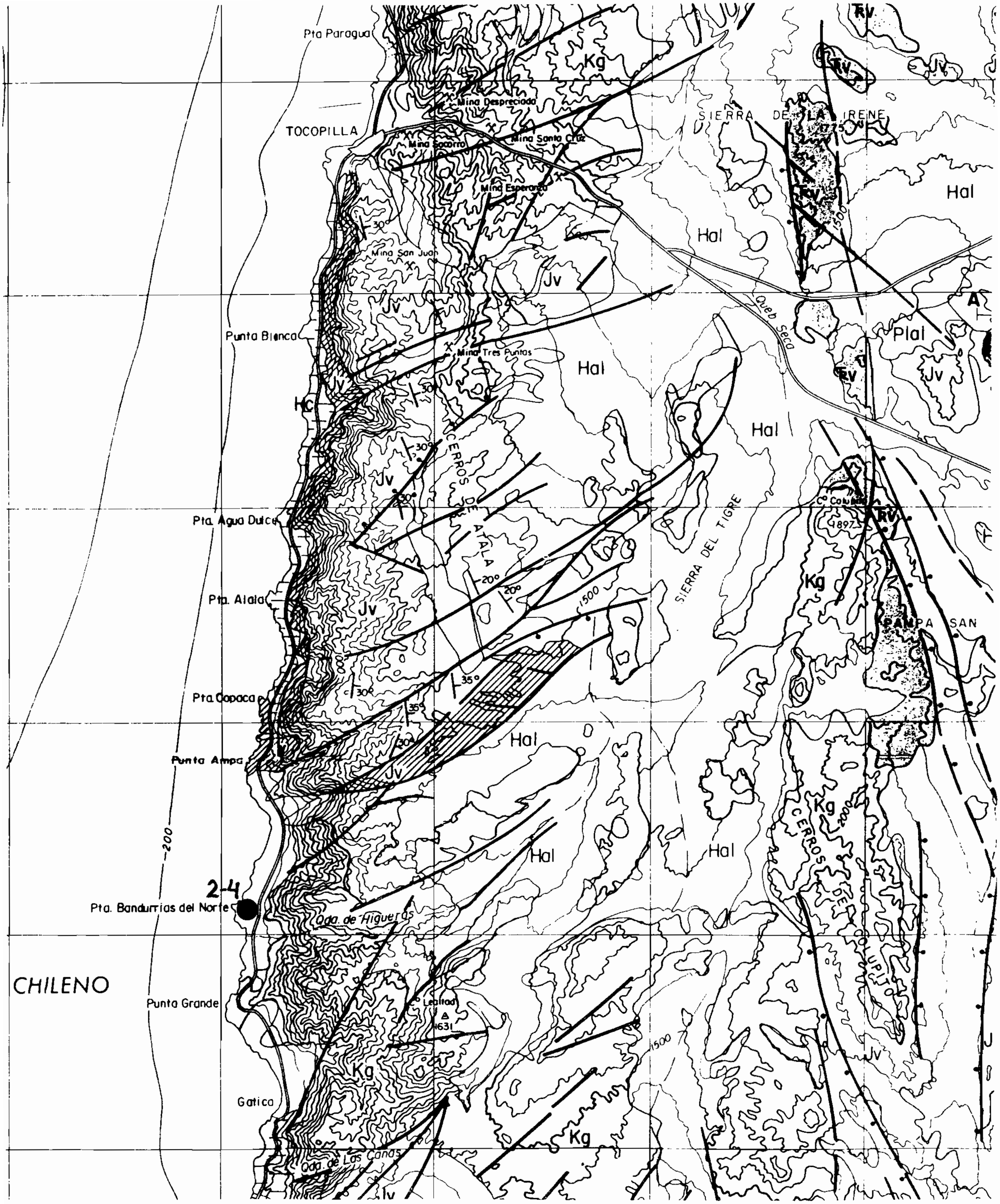


Fig. 2.0.2.- Localisation of the last stops of the second day, between Gatico and Tocopilla.

HORNITOS: UPLIFT MOTIONS OF THE COASTAL PLAIN IN THE LAST 300,000 Y.

At Stop 2.1 (Fig. 2.0.1), will be shown a sequence of staircased marine terraces that recorded the high sea stands of the last 300,000 y. We shall also have a look at the Holocene progradation of the shoreline.

THE SEQUENCE OF MARINE TERRACES AT HORNITOS

Extracts from the abstract of communication to the IGCP 367 meeting at Antofagasta:
«Quaternary coastal evolution of the Hornitos area (Northern Chile) in the last 300,000 years: Neotectonic interpretations. » (L. ORTLIEB, C. ZAZO, J. L. GOY, C. HILLAIRE-MARCEL & M. GHALEB).
(References to figures of this fieldguide were added.)

The locality of Hornitos **(Fig. 2.1.1 & 2.1.2)** is becoming a classical locality for the study of the marine Quaternary in northern Chile. Herm (1969) correlated the three conspicuous terraces of the area with the Serena I, Serena II, and Herradura I terraces identified in the Coquimbo-La Serena region **(Fig. 2.1.3)**. Radtke (1985, 1989) obtained the first geochronological results through ESR and U-series dating and suggested that the youngest Pleistocene terrace was of last interglacial age, while the two older terraces could be assigned to the Middle and/or Early Pleistocene **(Fig. 2.1.4)**. More recently, a detailed chrono- and morphostratigraphical study was undertaken at Hornitos, because the area offers a favourable geomorphological setting and because it is located on the northern reaches of the bay of Mejillones, thus making possible lateral correlations with the extensive beach-ridge sequence of Pampa Mejillones. In a preliminary report (Ortlieb et al., 1994), which included some aminoacid racemisation and a few U-series results (through α-spectrometry), we inferred that the lowest, most conspicuous, marine terrace at Hormitos, was probably of substage 5e age, the second more elevated one of isotopic stage 7, and the highest elevated terrace was possibly of isotopic stage 9 age. In that previous paper we hypothesized that immediately south of Hornitos (Chacaya), some low-lying marine terraces may be related to one or two younger Late Pleistocene high seastands corresponding to Isotopic Substages 5c and/or 5a.

The detailed morphostratigraphic study of the area between Punta Yayes and Chacaya, combined with photogeologic mapping as well as with 15 U-series measurements and some 115 amino-acid racemisation analyses, resulted in a more refined interpretation of the chronology of marine deposits associated with the last episodes of high sea-level stand. In most cases, the analytical results are internally consistent and coherent with the morphostratigraphic interpretation.

Despite frequent reworking from higher and older fossiliferous deposits, allo/isoleucine measurements (A/I) in *Mulinia edulis*, *Mesodesma donacium* and *Protothaca thaca* shells, data available from the Hornitos area suggest the following aminostratigraphic interpretations:

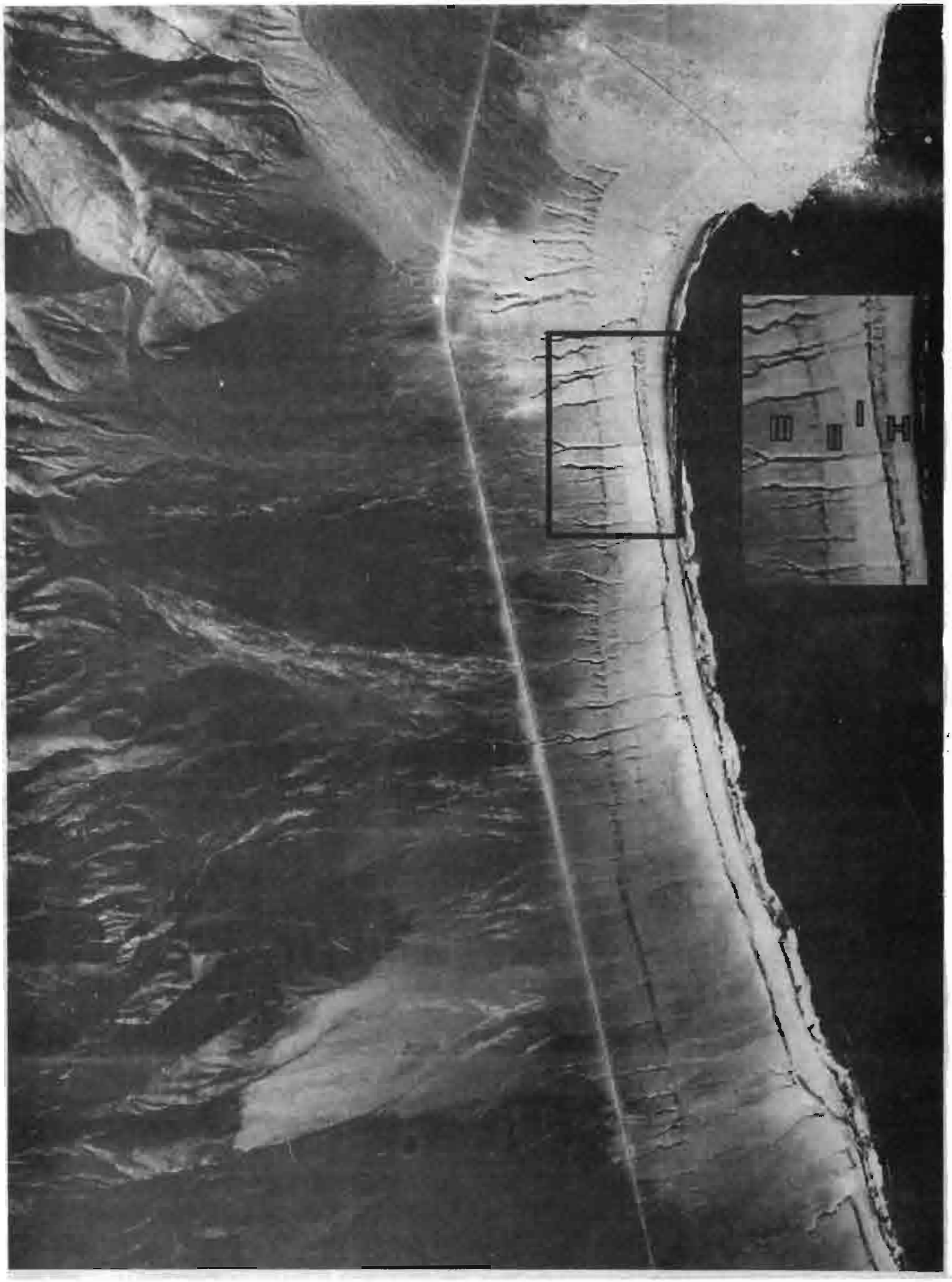


Fig. 2.1.1.- Aerial photograph of the area of Hornitos, with enlargement of a sector showing the staircased disposition of the Holocene and Pleistocene marine terraces (Serv. Aerofotogramétrico, SAF-81, CH60-S.5-3, 018962).

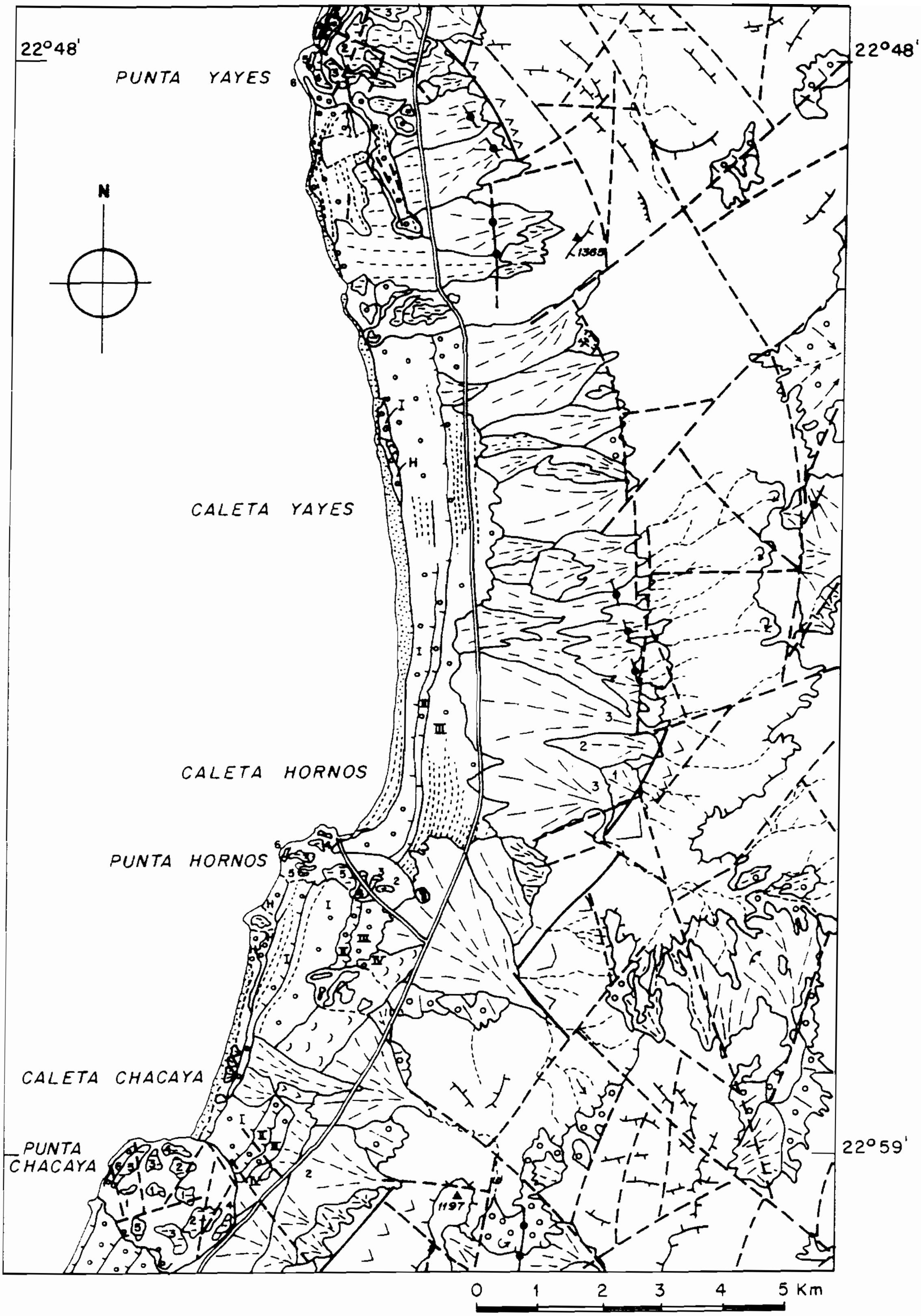
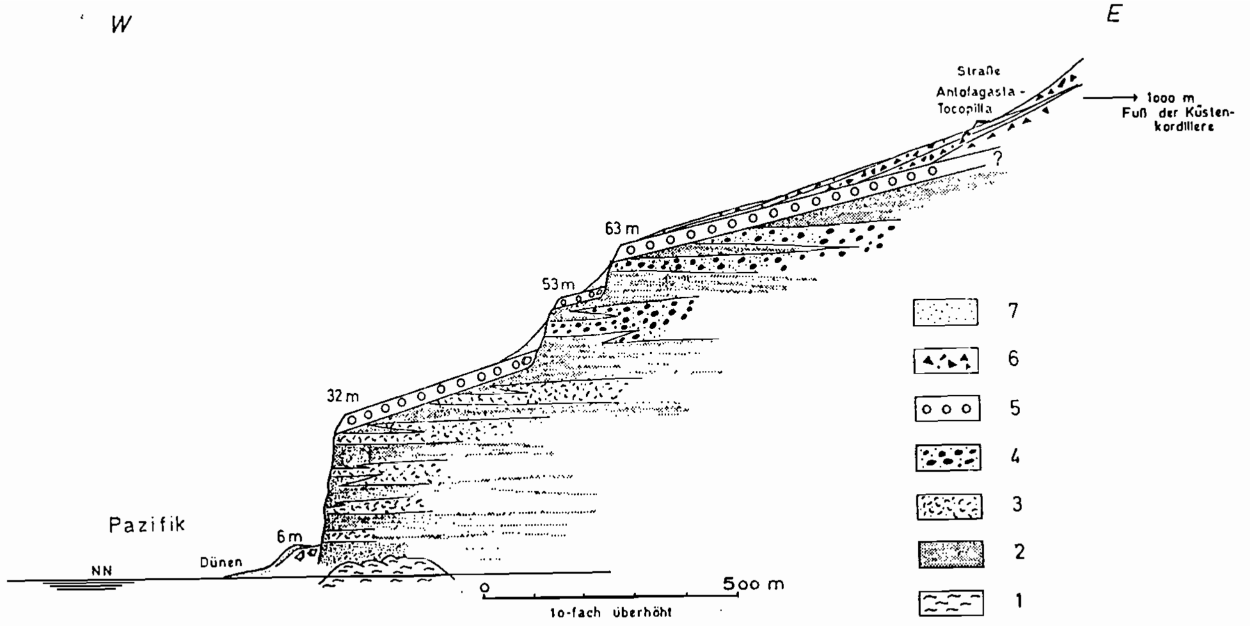


Fig. 2.1.2. - Geological sketch map of the area of Hornitos (See legend of Fig. 0.1.6). The marine terraces identified by « I », « II » , « III » and « IV » are assigned IS 5, IS 7, IS 9 and IS-older-than-9 ages, respectively.



E-W-Profil an der Caleta Playa de los Hornos, nördlich Hornito, (P-P auf Abb. 2): 1 = Mesozoische Vulkanite des Grundgebirges; 2 = Mittel- bis feinkörnige Sande, z. T. dünngebankt und verhärtet; 3 = Schalenschutt, schräggeschüttet und sich lagenweise mit Sanden verzahnend; 4 = Wenig sortierte, grobe Konglomerate; 2—4 = Pliozän; 5 = Grobe Regression-Sedimente des Pleistozän: Strandsande mit Geröllen und Schalenschutt; 6 = Hangschutt; 7 = Dünensande.

Fig.2.1.3.- Geological section of the three major terraces at Hornitos, according Herm (1969). Herm had proposed a correlation between the successive marine platforms (from oldest to youngest) with the Serena I, Serena II, and Herradura I terraces identified at Coquimbo-La Serena.

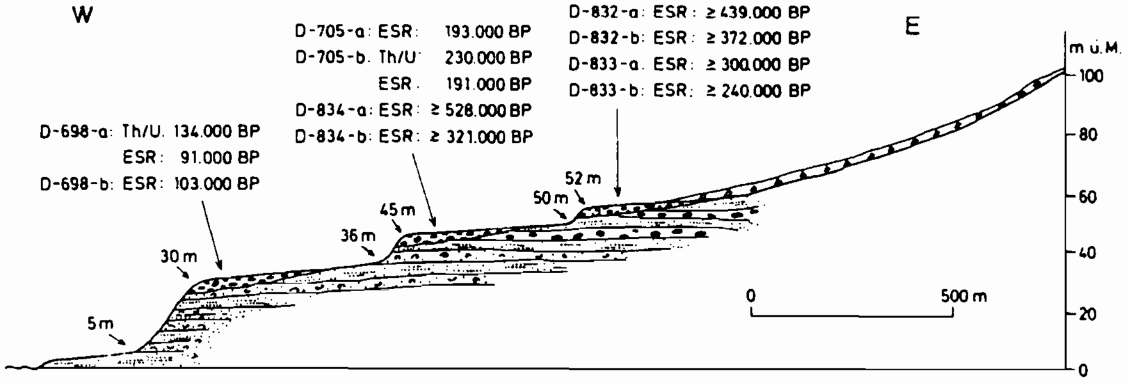


Fig. 2.1.4.- Geochronological results obtained by Radtke (1989) on the terraces of Hornitos.

clusters of A/I values of 0.36/0.42 would correspond to Isotopic Substage (IS) 5c, 0.49-0.51 to IS 5e, 0,61-65 to IS 7, 0,69-73 to IS 9, and 0,80 to IS 11 (**Table 2.1.1**). This regional aminostratigraphic scale is consistent with previous results we obtained in southern Peru (Ortlieb & Macharé, 1990, Ortlieb et al., 1992, 1996), but differs from the aminostratigraphic interpretation of Hsu et al. (1989) for northern Chile and southern Peru.

Mollusk shell samples from the outer edge of the lowest Pleistocene terrace (top of the Holocene seacliff, at +18/+25 m asl) were dated between 103 and 109 ka (5 apparent ages calculated from TIMS analyses). In several cases (albeit not all) where the TIMS U-series results point to younger than 125 ka ages, morphostratigraphic and A/I data also suggest a younger than IS-5e age (as the highest sestand of the last interglacial). In one locality, also from the lower terrace (Punta Yayes), mollusks provided U-series apparent ages of 116/124 ka and A/I ratios of 0.50: this locality is assigned an IS 5e age. Actually, geological and morphostratigraphic evidence indicate that the lowest marine terrace at Hornitos did register at least two sea level fluctuations (**Fig. 2.1.5**). In spite of its flat surface (due to the latest Quaternary alluvial cover), the first terrace of Hornitos recorded two late Pleistocene high seastands, that we propose to correlate with IS 5c and 5e. The +36 m elevation of the inner edge of the low terrace, which records the IS 5e highest stand of sea level, provides a mean uplift rate estimate of 240 mm/10^3 y (if it is assumed that the paleo-sea level was a few m above present datum). The remnants of the IS 5c high sea stand, found at up to +25 m, indicate that, if the regional uplift rate remained constant through time, the paleo-sea level would have been close to the present datum (and not as much as 10 m below, for instance).

The second higher marine terrace at Hornitos is the least developed of the three. It is much narrower than the other two and disappears in the northern part of the bay. Its maximum elevation varies between +50 and +63 m to the east and north-east of Hornitos (but is higher elevated to the south of Hornitos). Two episodes of high seastand were locally observed within the sedimentary cover of the terrace. Some A/I results and a single U-series apparent age support the morphostratigraphic interpretation of an IS 7 (7a and 7c) age.

The third higher terrace is very wide, particularly east of Hornitos. Its inner edge, hidden by the alluvial fans formed at the foot of the Coastal Cordillera, is at a higher elevation than +80 m. Numerous quebrada cuts perpendicular to the coast show that the thin sedimentary cover of this flat terrace consists in a series of prograding units of coarse beach deposits set in offlap (**Fig. 2.1.6 & 2.1.7**). A close cluster of A/I results (mean values: *P. thaca*= 0.73; *M. edulis*= 0.71; *M. donacium*= 0.69; *Venus antiqua*= 0.70) strongly suggests an assignment of the IS 9 (ca. 330 ka) to this locality (+75 m elevation). The A/I results support a lateral correlation with the deposits associated with the marine abrasion surface which cuts the Pliocene substrate at the northern end of Antofagasta Bay (La Portada), where apparent U-series ages of 280-290 ka were obtained. Furthermore, the lack of warm-water species in the molluscan fauna of the third terrace of Hornitos (**Table 2.1.2**). also supports a tentative assignment of these deposits to the marine transgression that predated the IS 11 (identified by the occurrence of *Trachycardium procerum* shells in Mejillones peninsula, Guzmán et al., 1995; Ortlieb et al., in prep.).

East of Chacaya, a narrow outcrop of coastal deposit, at an +100 m elevation,is interpreted as older than the third terrace of Hornitos. The oldest remnant of Pleistocene

Sample	Elevation (m)	Species	A/I	n	sigma	U/Th TIMS	U/Th	inter-pretation
HORNITOS								
C92-6	+ 25	*P. thaca*	0,36	3	0,02	105,3 ± 1,0		5c?
		M. edulis	0,42	2	0,01	108,3 ± 0,8		
		E. rufa	0,38	1		108,8 ± 1,0		
C92-10	+ 18	*P. thaca*	0,49	2	0,07	106,1 ± 0,8	124 ± 7,0	5e?
C92-10		*E. rufa*	0,51	2	0,02	109,2 ± 0,9	116 ± 6,0	
							106 ± 5,0	
							119 ± 5,0	
C92-11	+ 18	*M. edulis*	0,51	4	0,07			5e?
C93-83	+ 60	*M. edulis*	0,63	3	0,04			7
C93-83		*M. donacium*	0,61	3	0,04			
C93-80	+ 75	*M. edulis*	0,71	3	0,06			9
		P. thaca	0,73	3	0,05			
		M. donacium	0,69	3	0,05			
		V. antiqua	0,70	1				
CHACAYA								
C92-2	+ 23	*M. edulis*	0,47	3	0,05			5e
		M. donacium	0,46	3	0,03			
C94-108	+ 30	*M. edulis*	0,45	3	0,05			5e
		M. donacium	0,47	3	0,05			
		V. antiqua	0,53	3	0,02			
C93-85	+ 100	*P. thaca*	0,79	2	0,10			11?

Table 2.1.1.- Geochronological results obtained on mollusk shells from the marine terrace deposits at Hornitos (unpublished data from GEOTOP). U-series « apparent » ages were indicated only for two localities on the lower terrace (I), but they should not be taken at face value (without considering the whole set of analytical results).

Fig. 2.1.5.- The youngest Pleistocene marine terrace (I in Fig. 2.1.1) east of Hornitos, showing that, below the late Quaternary alluvium, two distinct coastal deposits are preserved. At left, the beach deposit is assigned to the IS 5c; at right (to the left of the persons) can be seen the sediments associated with the maximum of the last interglacial transgression (IS 5e). In the background, palaeo-seacliff cutting the second older terrace.

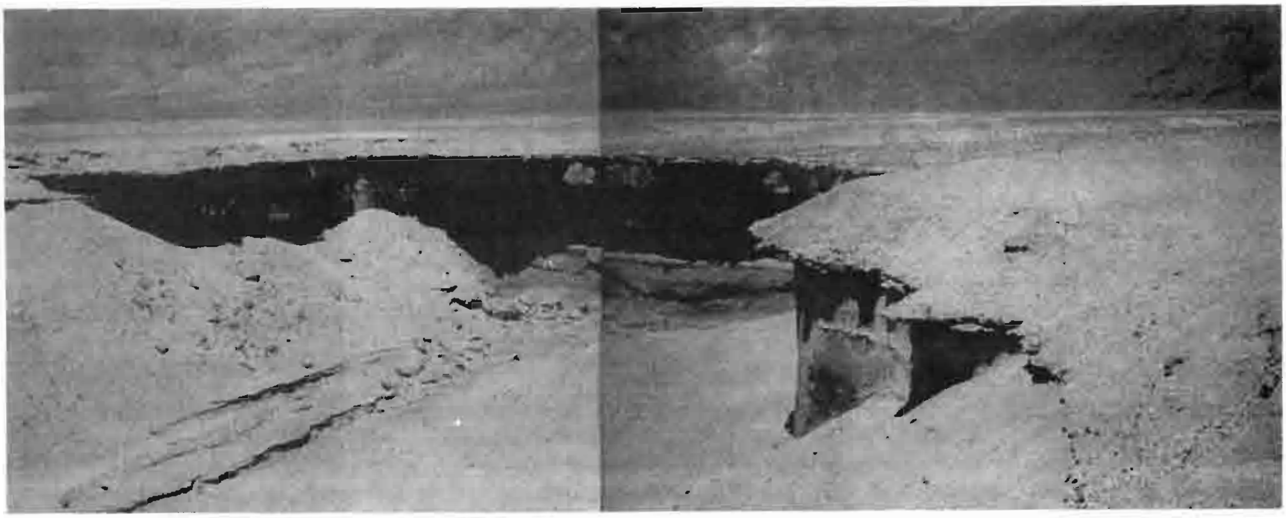


Fig. 2.1.6.- The thin marine deposits associated with the third older terrace (III in Fig. 2.1.1) east of Hornitos, at a +75 m elevation (Photo L.O.). These deposits are assigned an IS 9 (ca. 330 Ka) age (Table 2.1.2).

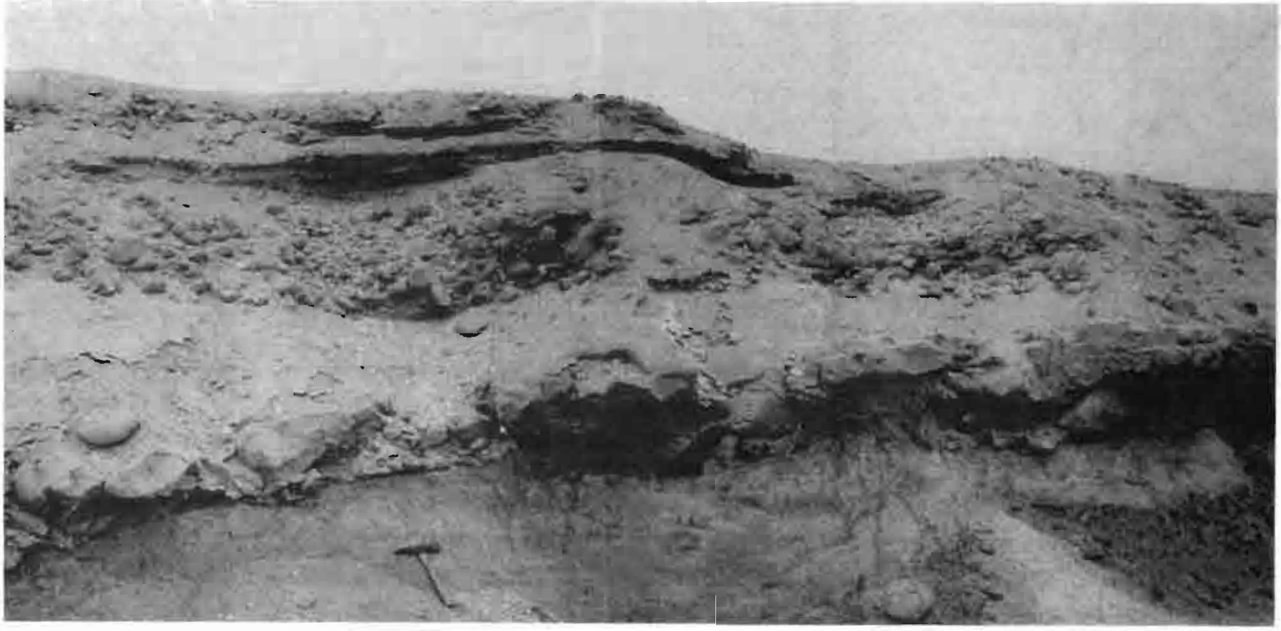


Fig 2.1.7.- Marine deposit of the third terrace at Hornitos (III in Fig. 2.1.1), on the east of the road toward Michilla (+90 m) (Photo L.O.).

HORNITOS

GASTROPODS :	Holoc.	IS 5	IS 7	IS 9
Aeneator fontainei	X	P	P	A
Calyptraea (T.) trochiformis	X	**V**	A	**V**
Cancellaria (S.) buccinoides	X	P		
Collisella spp.	X	P		
Concholepas concholepas	X	P	P	**V**
Crassilabrum crassilabrum	X	P		P
Crepidula spp.	X			P
Crepipatella dilatata	X	**V**	**V**	**V**
Crepipatella dorsata	X	P	A	**V**
Crucibulum cf. C. lignarium	X			P
Crucibulum quiriquinae	X	P	P	P
Fissurella crassa	X	P		
Fissurella latimarginata	X	P	P	P
Fissurella maxima	X	P		P
Fissurella peruviana	X	P		P
Fissurella spp.	X	P		P
Mitrella unifasciata	X			P
Nassarius gayi	X	P		P
Nucella (A.) crassilabrum	X	P	P	P
Oliva (O.) peruviana	X	P	P	A
Polinices (P.) uber	X	P		P
Priene scabrum	X	P	P	**V**
Prisogaster niger	X	**V**	P	**V**
Sinum cymba	X	**V**		P
Tegula (C.) atra	X	A		P
Tegula (C.) euryomphala	X	P		A
Tegula (C.) luctuosa	X	P		P
Tegula (C.) tridentata	X	P		A
Thais (S.) chocolata	X		P	P
Turritella cingulata	X	P	P	**V**
Xanthochorus buxea	X			P
Xanthochorus cassidiformis	X	P	A	P

PELECIPODS :	Holoc.	IS 5	IS 7	IS 9
Argopecten purpuratus	X	**V**	**V**	P
Aulacomya ater	X	P	P	P
Brachidontes granulata	X	P		
Chama pellucida	X	P		
Chione (L.) peruviana		P		
Choromytilus chorus	X	P	A	A
Cyclinella subquadrata		P		
Cyclocardia spurca		P		
Ensis macha	X	P		P
Eurhomalea lenticularis		**V**	**V**	**V**
Eurhomalea rufa	X	**V**	**V**	A
Glycymeris ovatus	X	**V**		P
Mesodesma donacium	X	**V**	A	**V**
Mulinia cf. M. edulis		**V**	A	**V**
Perumytilus purpuratus	X	P		P
Petricola (P.) rugosa	X	P		P
Pholas (T.) chiloensis	X		P	
Protothaca (P.) thaca	X	**V**	P	**V**
Semele solida	X	P		P
Semimytilus algosus	X			P
Tagelus dombeii	X	P	P	P
Transennella pannosa	X	P		
Venus antiqua		P	A	A

P: Present
A: Abundant
V: Very abundant

Table 2.1.2.- List of molluscan fauna of the deposits associated to the marine terraces at Hornitos and comparison with modern fauna of the area (determ. L.O. & N.G.).

Fig. 2.1.8. - Highest remnant of Pleistocene marine terrace in the area of Hornitos-Punta Yayes (E of Pta Yayes), at +170 m. In the foreground, eroded remnant of the marine abrasion surface. In the background, the clear line corresponds to an ashfall deposit interstratified into an alluvial sequence which postdated the marine transgression. (Photo L.O.).

marine transgression indentified in the area, was observed at a +170 m elevation due east of Punta Yayes **(Fig. 2.1.8)**.

The chronostratigraphic interpretation of the remnants of marine terraces in the Hornitos area suggests a relatively continuous uplift motion during the last 300,000 y, with a mean value of the order of 240 mm/10^3y (at least immediately east of Hornitos). Nevertheless some tectonic motions did occur since the end of the Middle Pleistocene in the region. Two fault systems oriented N120-140° and N20-30°, and a few N-S trending faults, were mildly reactivated, both north and south of Hornitos (Pta Yayes and Pta Chacaya). Two tectonic blocks can thus be distinguished: one in Caleta Yayes-Hornitos, and another one in Caleta Chacaya. The attitude of the Pleistocene shorelines in the whole study area points to a small-amplitude tilt, toward the south, of each block (except may be during the IS 7 period). The tilt motions of the faulted blocks are interpreted as minor readjustments linked to the active deformation which has been occurring in the half-graben of northern Mejillones Peninsula, for the last several hundred thousand years.

At Stop 2.2 (Fig. 2.0.1), we shall examine:

- an anomalously elevated coastal deposit of Holocene age (is it a tsunami deposit?), and
- another sequence of emerged Pleistocene terraces, and particularly the fossiliferous deposits associated to the most recent terrace (IS 5c).

Some considerations regarding the recent disappearance in northern Chile of the most commonly found pelecypod (*Mulinia* cf *M. edulis*) in the Pleistocene coastal deposits will also be made.

MICHILLA: THE +7 m ELEVATED HOLOCENE COASTAL DEPOSIT

Michilla Bay is the only known locality in northern Chile where Holocene coastal deposits are reaching an elevation higher than +6 m. This exceptional deposit forms a narrow terrace (50 m wide, 1 km long) in the innermost (protected) part of a small embayment (Fig. 2.2.1). An on-going (rapid?) progradation of the shoreline is attributed to the recent input of mining refuse material to the coastal zone. The sediment accumulation in the embayment played a major role in the preservation of the +7 m deposit, but does not explain by itself how and why the fossiliferous Holocene coastal sands and gravels were deposited at the foot of the old seacliff. Is the attitude of this deposit the result of a tectonic uplift (with or without faulting activity), or an exceptional sedimentary accumulation ?

A tsunami, or storm, deposit ?

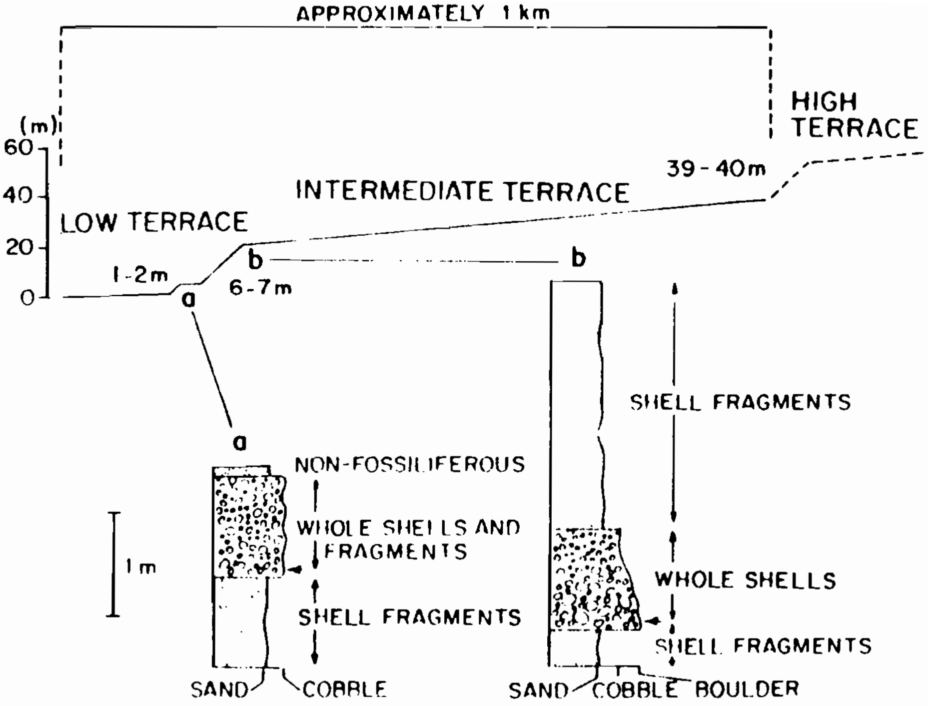
The sandy deposit contains gravels and shingles, and a relatively abundant molluscan fauna with many unbroken large shells. The sediment texture and stratigraphical characteristics of the deposit are not typically those of a storm deposit which would have been accumulated at the base of a former seacliff. On another hand, the distribution of the shingles within the sand and the taphonomy of the shells do not suggest that it is a subtidal (or intertidal) deposit, which would have been uplifted (in a way or another) afterwards.

It is suggested here that the Holocene deposit might be related to a (brief ?) episode of high seastand during the peak of the Holocene sealevel maximum, possibly a tsunami event. Comments from colleagues who studied tsunami deposits in other parts of the world would be welcome.

Age of the Holocene deposit

The age of the deposit is provided by radiocarbon and U-series dating. In 1991, Leonard & Wehmiller published a ^{14}C age of 6725 ± 95 BP (GX-15475) obtained on a single *Mulinia* shell. These authors also measured an allo/isoleucine mean ratio of 0.16 ±0.03 on three *Mulinia* shells from the same bed (Fig. 2.2.2). Another (unpublished) radiocarbon date of 6990 ±80 BP was obtained, in 1994, at GEOTOP laboratory on *Mulinia* and *Mesodesma donacium* shells. U-series measurements (by Thermal Ionization Mass Spectrometric method) on shells from the same upper layer of the deposit provided ages of 7.1 ±0.1 and 7.2 ± 0.2 ka (^{230}Th/^{234}U= 0.0635, Fig. 2.2.3). The internal consistency of these radiometric results should be noticed.

Fig. 2.2.1.- The anomalously high Holocene (7 000 BP) marine deposit at Michilla.. Above: view from the village towards N. Below: Top of the Holocene deposits is at +7 m a.MSL (Photos L.O.).



Genus	**A/I Value**	**^{14}C Age**
a. Shells from the Low terrace at Caleta Michilla (6-7 m above modern sea level)		
Mulinia	*0.125*	*6,725 +/- 95*
Mulinia	*0.152*	
Mulinia	*0.190*	
b. Shells from the Intermediate terrace at Caleta Michilla (39-40 m above modern sea level)		
Protothaca	*0.39*	
Protothaca	*0.41*	
Protothaca	*0.56*	
c. Shells from the 43 m terrace at Punta Tames		
Protothaca	*0.390*	
Protothaca	*0.392*	
Protothaca	*0.401*	

Note. The number of significant figures given for A/I values reflects our evaluation of the precision and accuracy of measurement of chromatograms for each sample.

Fig. 2.2.2.- Geochronological results obtained by Leonard & Wehmiller (1991) on Holocene and Late Pleistocene marine terraces in the area of Michilla-Pta Tames.

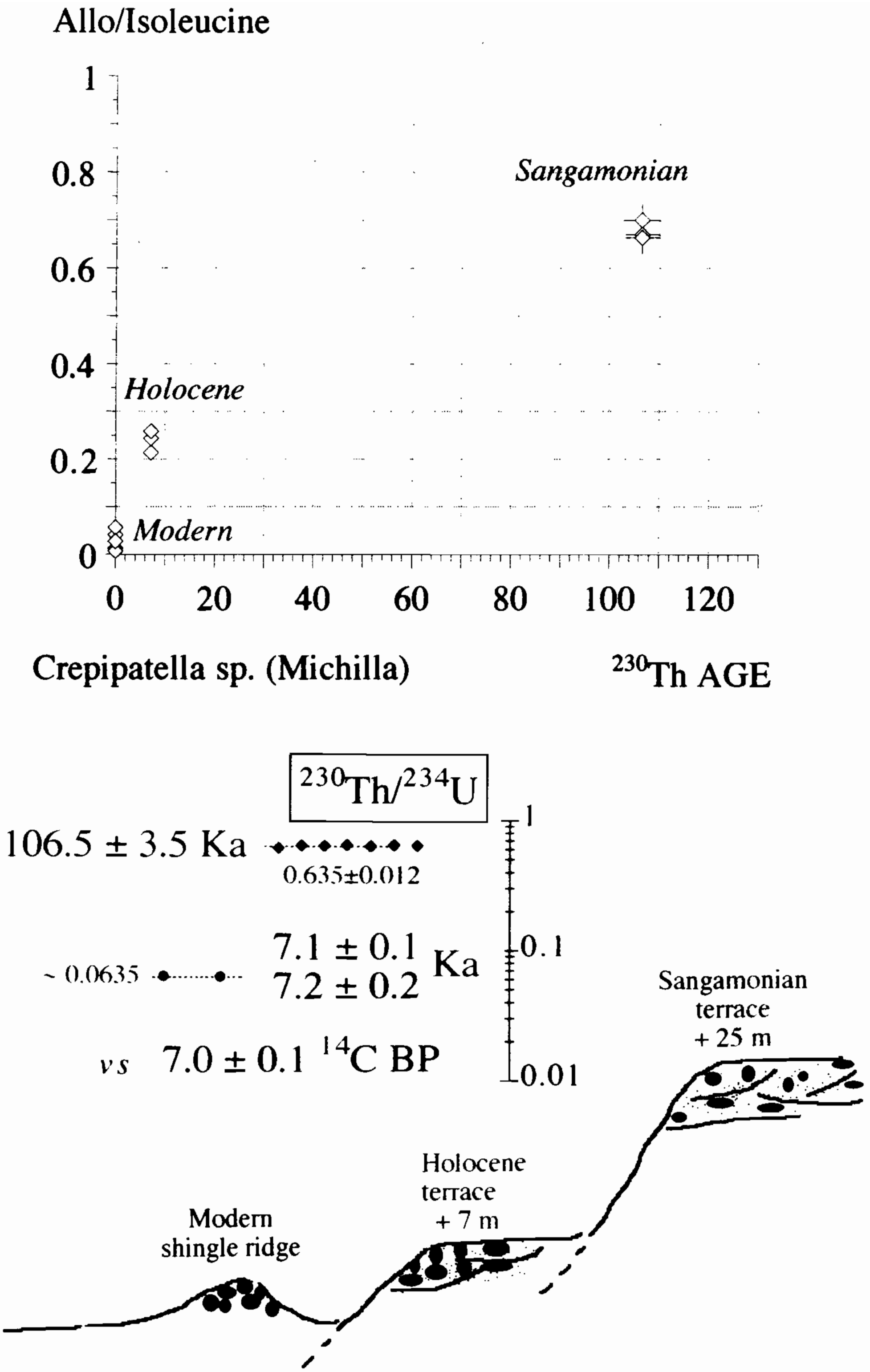


Fig. 2.2.3.- Geochronological results obtained on Holocene and Late Pleistocene marine terraces in the area of Michilla.

As scarce data from central Peru (Wells, 1989) (Fig. 2.2.4) and elsewhere suggest that the maximum of the Holocene seastand occurred at 7 000 BP, there is little doubt that the Michilla deposit is coeval with the peak of the last transgression.

Paleontological/paleoecological problem of the distribution of *Mulinia* cf *edulis*

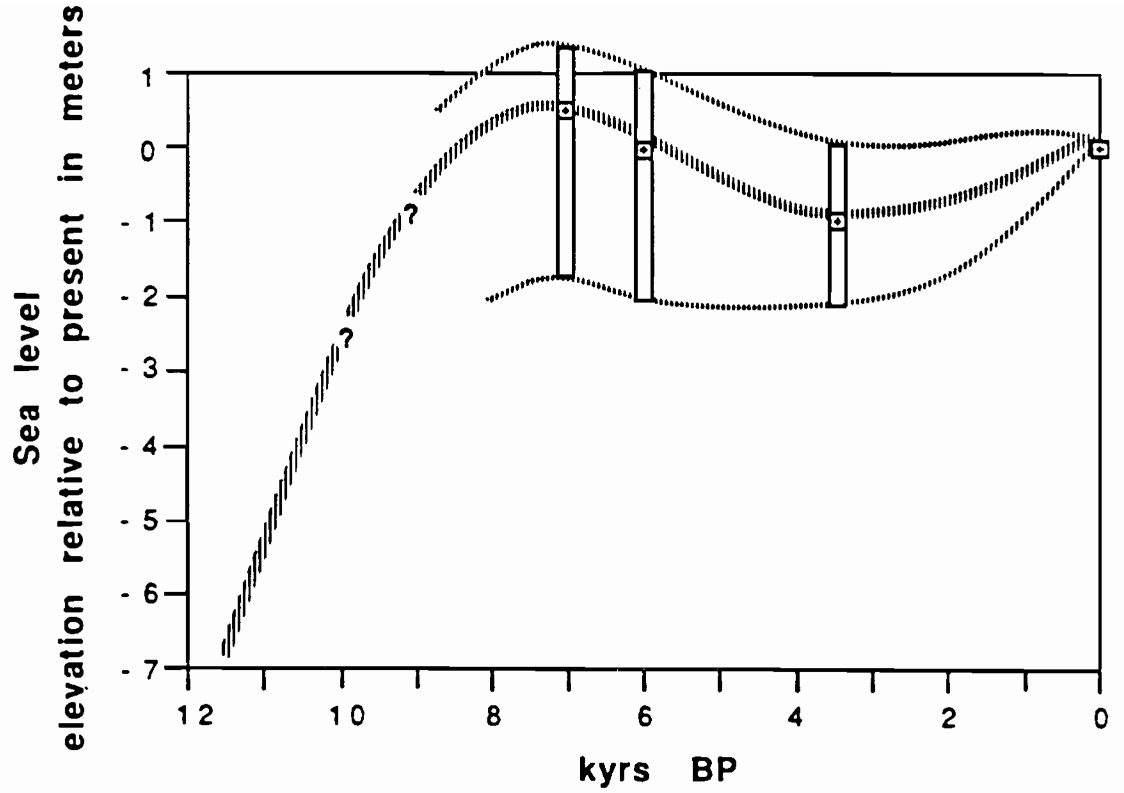
The Michilla Holocene terrace is also the only known locality where the bivalve shell *Mulinia* cf *edulis* has been found in a coastal sedimentary deposit in northern Chile. This species used to be the most common pelecypod in many places of the central and southern Peru coast, as well as in northern Chile during the Middle and Late Pleistocene. It is a typical opportunist species of sublittoral sandy areas (either in open oceanic conditions or in shallow embayments). It is generally found in very abundant quantities, as beachworn accumulations, in marine terrace deposits of the southern Peru - northern Chile area. Presently it is not found, even as small patches in the area.

The species disappeared almost completely in the Holocene record north of the Coquimbo-La Serena area, for some still unknown reason (Devries, 1986; Ortlieb et al., 1990, 1994; Ortlieb & Diaz, 1991; Ortlieb & Guzmán, 1994). The importance of the diminution of its geographic range (of the order of 3,000 km) must be noticed. The presence of the species at Michilla around 7,000 BP indicates that the dramatic shrinking of its distribution range occurred during the Holocene, and not coevally with some oceanographic or ecological alteration during the latest Pleistocene. The comparison of the faunal content of the Pleistocene marine terraces (Table 2.2.1) and of the Holocene/present-day mollusk assemblages (Ortlieb et al., 1990, 1994; Ortlieb & Diaz, 1991; Ortlieb & Guzmán, 1994; Guzmán et al., 1995) strongly suggests that the strong southward shift of the present distribution area cannot be attributed (only?) to temperature changes : there is no clear indication of either warmer, or cooler, conditions between the last three Pleistocene interglacials (isotopic stages 9, 7 and 5) and the present interglacial period. Thus some biological factor proper to *Mulinia* cf *edulis* may be involved.

The problem of the temporal variation in the geographic distribution of the species *Mulinia* cf *edulis* bears some similarities, as far as diachronic biogeographic processes are concerned, with the sudden appearance of *Strombus bubonius* in the Mediterrannean Sea during the isotopic stage 7 and its subsequent disappearance at the end of the last interglacial. In both cases, it seems that biological phenomena, possibly combined with some particular paleoceanographic circumstances, permitted the strong and « sudden » development (*S. bubonius*), or disappearance (*M.* cf *M. edulis*) of a dominant species.

GEOCHRONOLOGY OF THE LOWER TERRACE

Michilla is another locality in which U-series and aminostratigaphic data were obtained recently (Hillaire-Marcel et al., 1995) (Fig.2.2.3). The combination of morphostratigraphic and geochronological information leaves no doubt on the assignment of the lower marine terrace (inner edge at ca. +40 m) to the last interglacial, but it remains difficult to be more accurate, when one try to distinguish between 5c and 5e episodes (either with aminostratigraphic or with U-series measurements). Geomorphologically, the lower terrace at Michilla displays two platforms which would logically be assignable to the IS 5e and IS 5c episodes (Fig. 2.2.5).



. A relative sea level curve for the north central coast of Peru. The curve is developed on the basis of the morphology and exposed sediments at the Santa beach ridge complex (see also Figure 11). A model relating beach ridge morphology and sea level history is presented in the text. Squares (⊡) denote data points for which radiocarbon ages have been determined. Large rectangles denote the approximate error range in the determination of sea level at the dated localities. The two bounding curves denote the approximate error range for the sea level curve itself. The apparant drop in sea level between 7000 and 3500 BP may actually reflect uplift of the oldest bay floor owing to post-depositional salt crystallization in this area; the elevation error bars for the bay-floor locations have been extended to account for the possible uplift of this area.

Fig. 2.2.4.- Relative Holocene sealevel curve in north-central Peru (10°S) proposed by Wells (1988). According this interpretation, the highest position of sealevel during the Holocene would have occurred at ca. 7,000 BP and would have reached a few dm (less than 1.5 m) above present datum.

MICHILLA	**Holoc. 7000 BP**	**Late Pleist. (I.S.5)**	**Middle Pleist.**	**Early Pleist.?**
Elevation	+7 m	+20 m	+60 m	+160 m
Samples	C93-55/56	C93-57/58	C93-60	C93-61
GASTROPODS :				
Bulla sp.			P	
Calyptraea (T.) trochiformis		P	A	
Collisella orbignyi	P			
Concholepas concholepas	P	A	A	P
Crassilabrum crassilabrum		P	A	
Crepipatella dilatata	V	V	A	
Crepipatella dorsata		A	P	
Diodora cf. saturnalis				P
Fissurella crassa	P		P	
Fissurella latimarginata	P	P		
Fissurella limbata	P	P		
Fissurella maxima			?	
Fissurella peruviana	P	P	P	
Fissurella spp.	P	P		P
Nassarius gayi		P	P	
Nucella (A.) crassilabrum	P	A	P	
Oliva (O.) peruviana	P	P	P	
Priene scabrum		P	P	
Prisogaster niger	P	V	P	
Scurria parasitica			P	
Scurria scurra		P	P	
Scurria viridula	P	P		
Tegula (C.) atra	P	P	P	P
Tegula (C.) tridentata		P	A	
Turritella cingulata	P	A	V	p
Xanthochorus buxea		P	P	
Xanthochorus cassidiformis				P

PELECIPODS :

Argopecten purpuratus	P			
Brachidontes granulata	P			P
Choromytilus chorus	P	P		
Eurhomalea lenticularis	P?	?		
Eurhomalea rufa		V	P	
Gari solida			P	P
Glycymeris ovatus			P	P
Mesodesma donacium	V			
Mulinia cf. M. edulis	V			
Protothaca (P.) thaca	P	V	V	P
Semele solida		P	P	
Tagelus dombeii	P			

Table 2.2.1.- List of molluscan fauna of the deposits associated to the Quaternary emerged marine terraces at Michilla, including those dated 7,000 BP (Holocene) (determ. L.O. & N.G.).

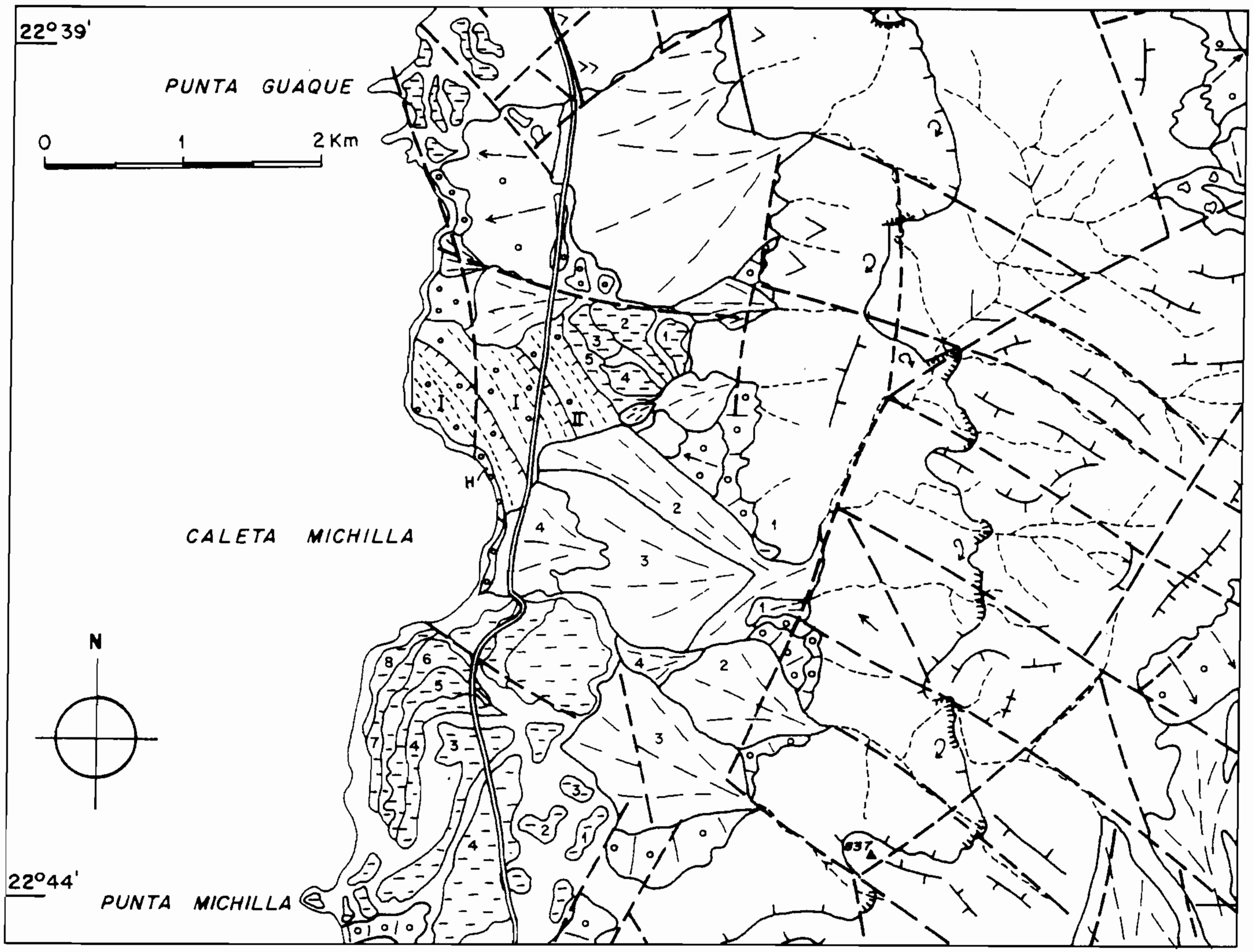


Fig. 2.2.5.- Geological sketch map of the area of the Michilla-Pta Guaque (See legend of Fig. 0.1.6). The marine terraces identified by « I » and « II » are assigned IS 5 and IS 7 ages, respectively. Within the marine terrace I, a small scarp separates the remnants of IS 5c and 5e transgressions. Letter « H » in Caleta Michilla indicates the anomalously high (+ 7 m) Holocene coastal deposit.

The stop at Cobija (Fig. 2.0.1) will be at the northern end of the small village, close to the beach and near the « aguada » (natural spring) called Tres Palmas, dug out in the early Holocene seacliff. At Cobija, the field party will observe:

- an *« aguada »* (natural spring) among those which permitted to the first inhabitants to survive in the hostile and completely dry environment of the coastal Desert of Atacama;
- the outer edge of a Late Pleistocene marine terrace, with very large rounded blocks;
- remnants of the destruction of the small town in 1877, as a consequence of the tsunami that affected the northern Chilean and southern Peruvian coasts; some deposits possibly linked to the proper 1877 tsunami will be seen;
- possible remnants of former and higher tsunami waves in archaeological deposits.

THE « AGUADAS » ON THE HYPER-ARID COAST OF NORTHERN CHILE

The water in the *aguadas* is infiltrated water which is stocked in natural reservoirs. The ultimate origin of this water has been traditionally attributed either to trapped atmospheric humidity (*camanchaca*) in the upper part of the Coastal Scarp, or to infiltrated groundwater from the central valley (Pampa del Tamarugal) which would have crossed the Cordillera de la Costa along a network of fracture zones (Nuñez & Varela, 1967-68, Sanchez, 1974a, 1974b).

At Cobija, the long-known *aguadas* have provided water to the coastal inhabitants for at least several thousand years, as evidenced by the remnants of human occupation. The main *aguadas* at or near Cobija are: Las Cañas, Algarrobo, and Tres Palmas. Hydrochemical analyses of the water provided by the *Aguada* Algarrobo indicated a pH of 6.5, 8.4 g/l of insoluble matter and 3.8 g/l chlorides, which makes it salty and not precisely appropriate for human use (Bittman & Alcaide, 1980).

The *Aguada* Tres Palmas was habilitated in a small cave carved in the Jurassic La Negra Fm., below the Late Pleistocene marine platform, and lays at only a few metres above sea level (Fig. 2.3.1).

THE LATE PLEISTOCENE MARINE TERRACES AT COBIJA

The upper part of the village of Cobija was built atop a marine platform assigned to the Late Quaternary (on geomorphological grounds). The outer edge of the terrace, at the top of the Holocene (inactive) seacliff, lies at between +8 and +12 m (Fig. 2.3.1) . Upon the platform a thin marine deposit is preserved locally. It is formed by very large boulders and blocks, similar to those observed on the present intertidal area, and a well-cemented sandstone with very little fossiliferous remains. The blocks were brought by alluvial floods, and were subsequently rounded by wave action, and finally accumulated on the Late Pleistocene and Holocene wave-cut platforms.

At 300 m north of the northernmost house of the village, can be observed a younger marine platform cut into the main Cobija terrace. The inner edge of that young marine wave-cut surface is found at +8 m, while the outer edge of the older one is, at that point +15 m high (Fig. 2.3.2). It is inferred that the younger transgression corresponds to the

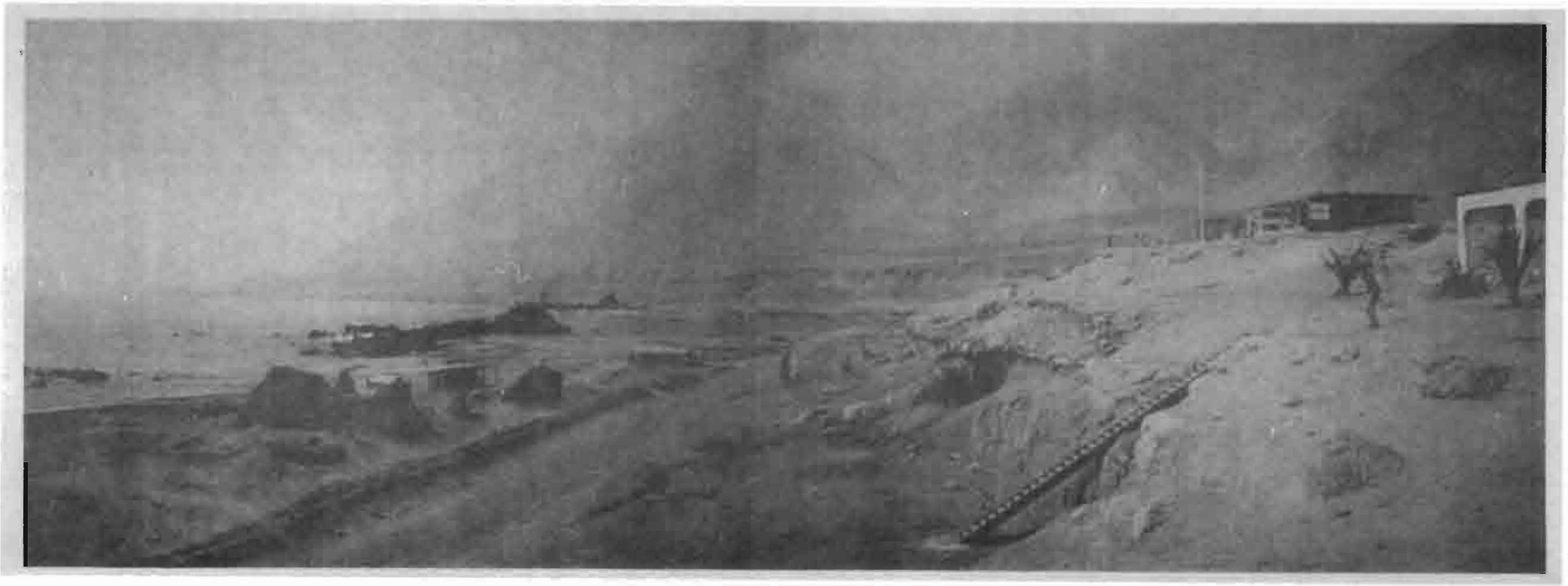


FIg. 2.3.1.- Northern end of the village of Cobija (view towards the N), showing from left to right: ruins left by the 1877 tsunami, the early Holocene seacliff with the spot of vegetation indicating the localization of the Aguada (spring) Tres Palmas, the outer edge of the Late Pleistocene marine terrace, and an archaeological site (below the house in the background) (Photo L. O.).

isotopic substage 5c (or 5a?), while the main terrace would be of isotopic substage 5e age. The lower marine terrace is covered by a thin sandstone unit (which was deposited in the supratidal area) and by a few meter thick alluvial sediments. These late Quaternary continental deposits are the latest sediments accumulated on the alluvial fan system, at the foot of the Coastal Scarp (Fig. 2.3.3). It may be mentioned that D'Orbigny visited Cobija in 1830, and left a drawing reproduced in Fig. 2.3.4.

TSUNAMIS IN NORTHERN CHILE

The « big bend » area at the boundary between Peru and Chile « has the highest seismic and tsunamogenic potential of any region along the coast of South America » (Lockridge, 1985). The last two major tsunamis which struck the northern coast of Chile occurred in 1868 and 1877. They provoked hundreds of deaths and left long-lasting effects in the collective mind of the coastal population. Prior to these two XIXth century events, tsunamis already had destroyed Arica twice in historical times, in 1604 and 1705. Several studies were dedicated to the historical earthquakes and tsunamis in southern Peru and northern Chile (Montesus de Ballore, 1912; Lomnitz, 1970. Silgado, 1974; Lockridge, 1985; Kausel, 1986; Dorbath et al., 1990; Monge & Mendoza, 1993). In Fig. 2.3.5 and Table 2.3.1, taken from Lockridge (1985), are listed and located the epicentres of the historical tsunamigenic seisms of northern Chile since 1615.

The recurrence of strong seismic tsunamigenic events in northern Chile has been estimated at 88 to 133 years (Nishenko, 1985, Comte et al. 1989; Dorbath et al., 1990; Kausel & Campos, 1992). In the Antofagasta Province the last relatively strong earthquakes, like the 1918 (December 4) and 1966 (Dec. 28) events (both Ms 7.8), or the fairly recent seism of July 30, 1995 (Ms 7.3), induced only small tsunami waves.

The 1868 and 1877 tsunamis

The 1868 tsunami has been described as possibly the most destructive tsunami of all times (Lockridge & Smith, 1984). On the 13th of August, 1868, the epicentre of the Ms 8.5 earthquake was located close to Arica (18°S, 71°W) (Lockridge, 1985). About half an hour after the main shock, the sea rose a first time by some five meters, then withdrew and left dry the nearshore area on a 2 km large strip. A second wave was produced several minutes later and, this time, reached an elevation of 15-18 m, or 21 m , according to the authors. At Iquique the major wave seemed to have reached 12 m.

In 1877, the epicentre of the Ms 8.25 earthquake (May 9) was located near Pabellon de Pica (19°S, 70° W). The runup of the tsunami wave was estimated to 20 m in Arica, 6-10 m in Iquique, 24 m in Tocopilla, 21 m in Mejillones and 6 m in Antofagasta.

Fig. 2.3.6 and 2.3.7 show the extent of the coastline affected by the 1868 and 1877 tsunamis. Tables 2.3.2. and 2.3.3. indicate the effects and runup of these and other tsunamis generated in northern Chile (including effects outside Southern America).

Remnants of the 1877 tsunami at Cobija

At Cobija, eyewitness sources (cited by Silgado, 1992, p.79-81) indicate that during the 1877 event, the sea rose quietly about five minutes after the major shock, up to an elevation of 11.9 m (above MSL) (according to the newspaper *Nacional*, from Lima, the runup was 9.4 m). The inflow destroyed all the lower part of the small town. Three

Fig. 2.3.2.- Late Pleistocene marine terraces at the northern extremity of Cobija village. The lower marine platform (above the jeep), with an inner edge at +8m, is interpreted as formed during the IS 5c (105 ka) or 5a (80 ka). The upper terrace, at the right, was probably carved during the maximum of the last interglacial high seastand (IS 5e, 125 ka). At this locality the IS 5e marine surface lies at about +15 m, but this altitude decreases toward the south (toward the peninsula of Cobija). (Photo L. O.)

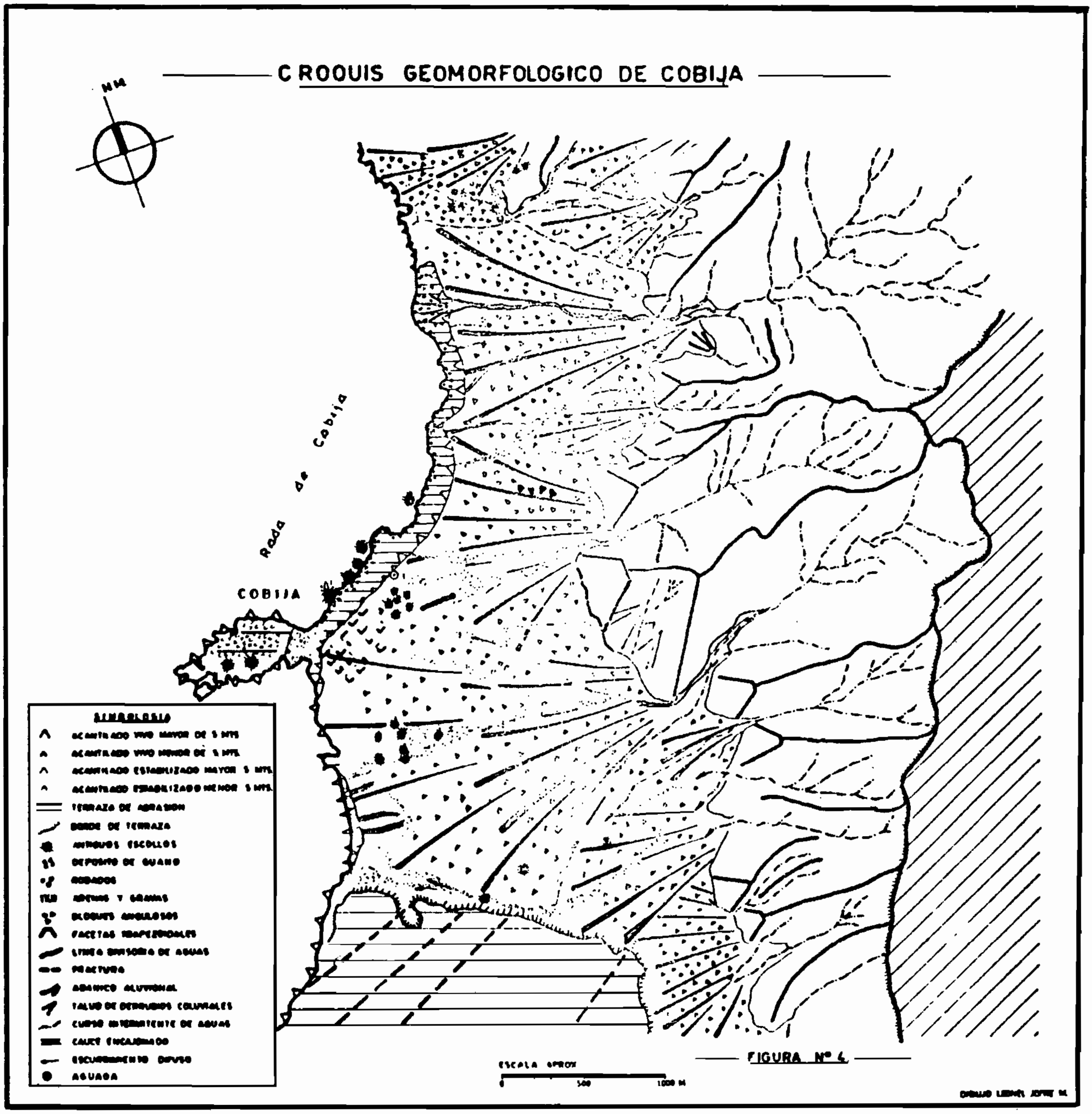


Fig. 2.3.3.- Geomorphological sketchmap of the area of Cobija, from Lagos (1980), showing the large development of alluvial fans at the foot of the Cordillera de la Costa.

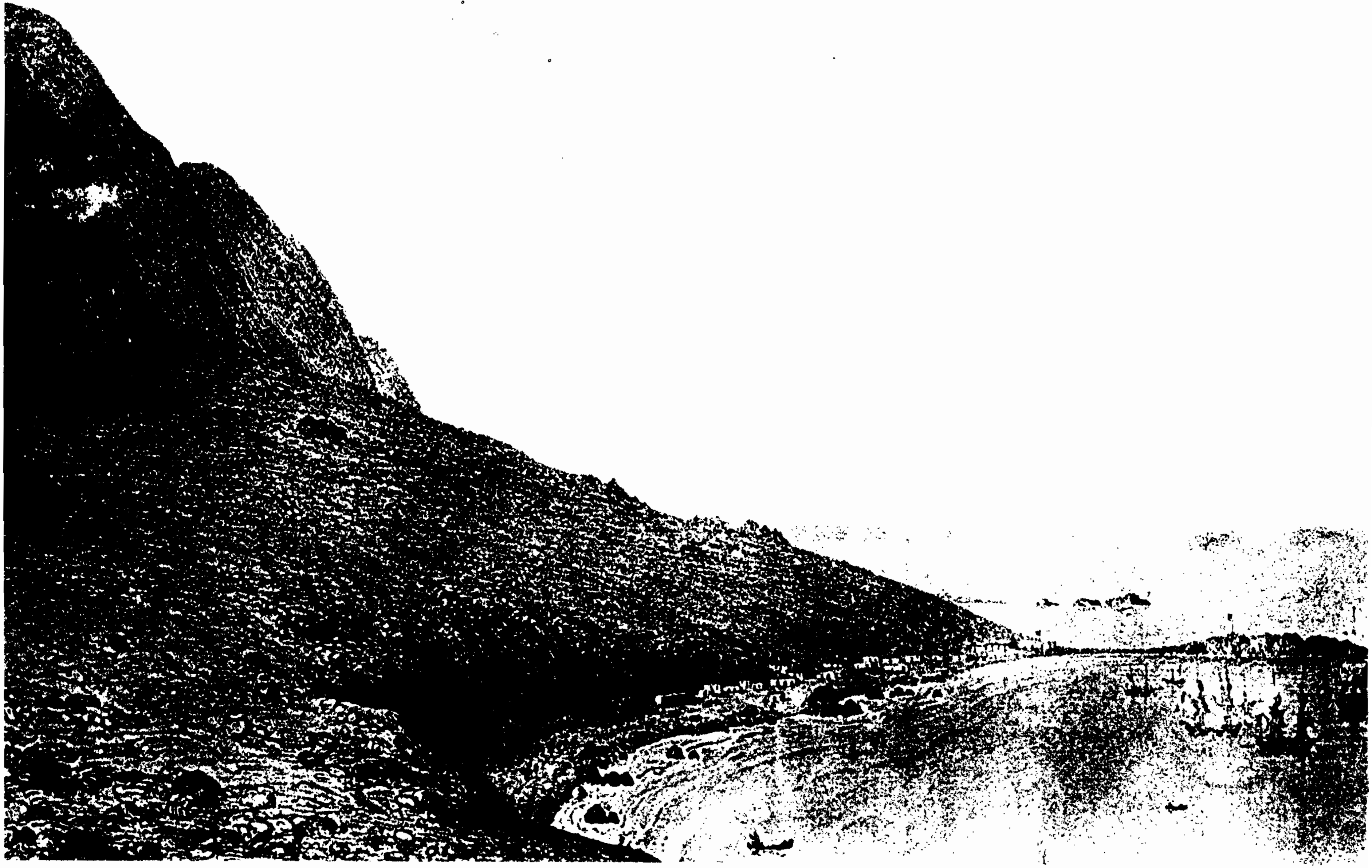


Fig. 2.3.4.- Sketch drawn by Alcides d'Orbigny, when he visited Cobija, in 1830 (d'Orbigny, 1958). It must be noted that the slope of the alluvial fans is exagerated in this sketch.

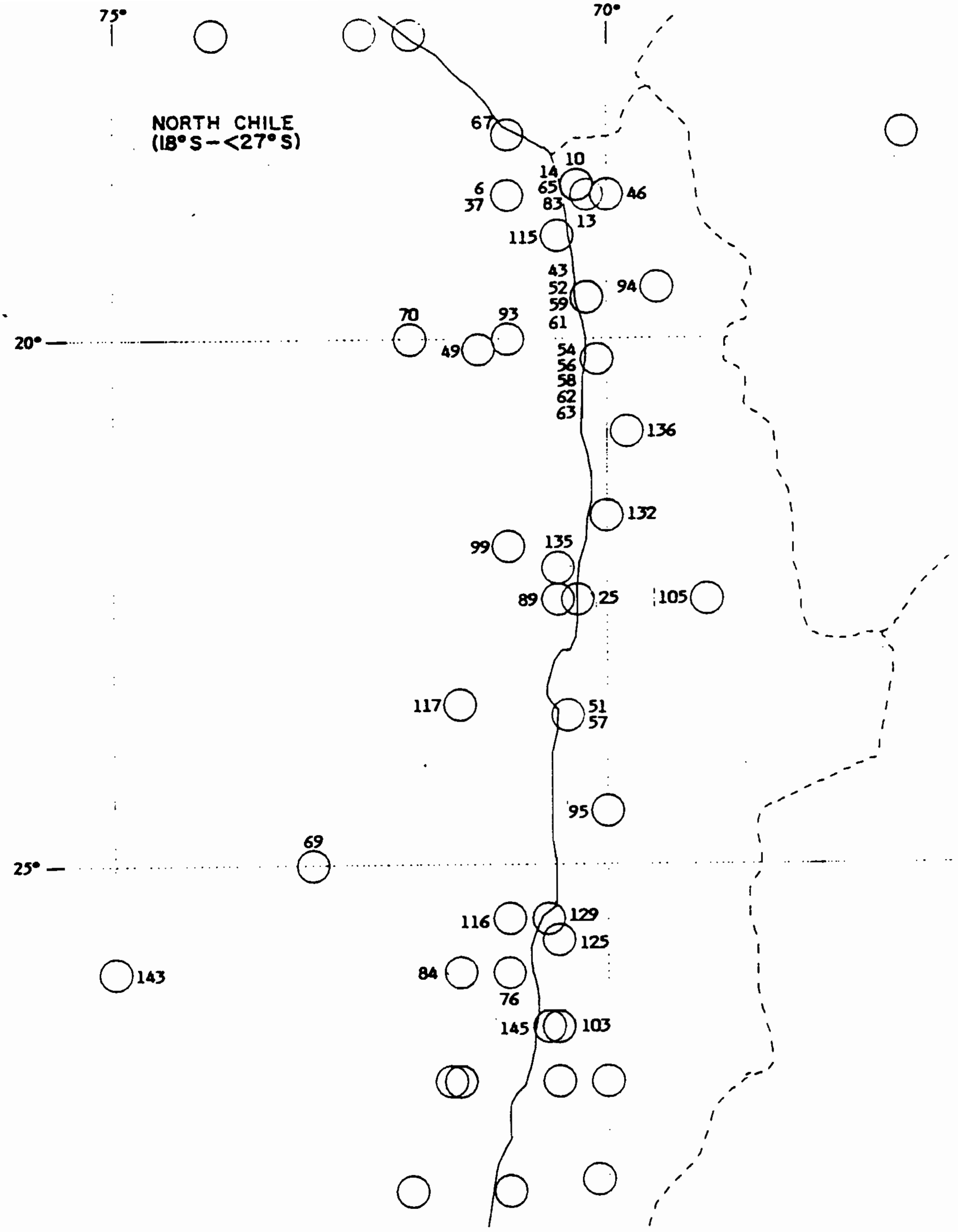
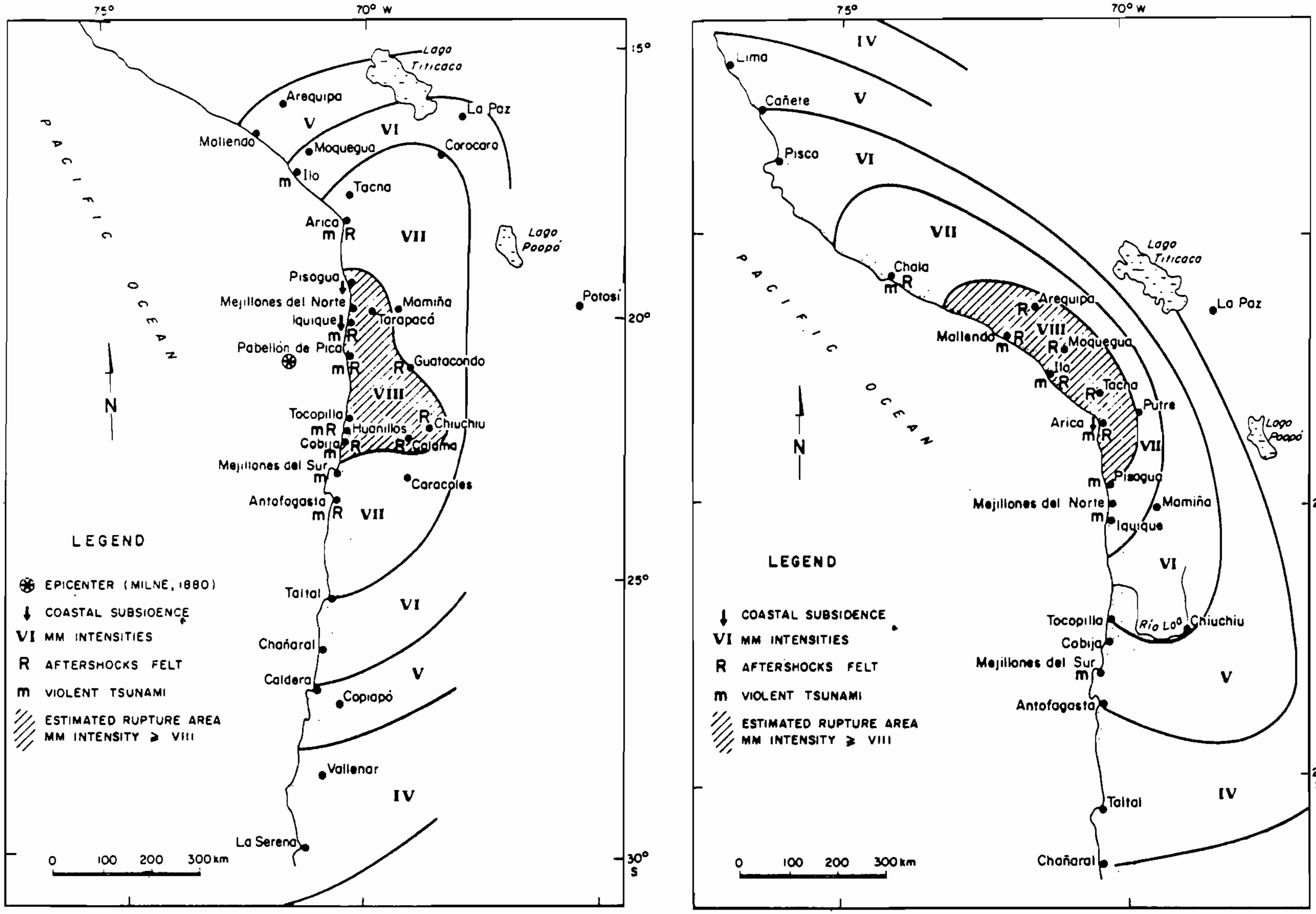


Fig. 2.3.5.- Localisation of the epicentres of tsunamigenic earthquakes in northern Chile (from Lockridge 1985). Numbers refer to the earthquakes listed in Table 2.3.1.

EVENT NO.	EVENT DATE YEAR MO DA	TIME	EARTHQUAKE DATA S. LAT. °	W. LONG. °	MAGNITUDE	DEPTH (KM)	TSUNAMI DATA RUNUP (M)	MAGNITUDE	INTENSITY	VALIDITY	REFERENCES
6	1615 09 16	2400	18.6	71.0	7.5		4.0	2.0	1.5	4	1,9,10,31,38,51
10	1681 03 10		(18.5	70.3)	7.5					3	31,51
13	*1705 11 26		18.6	70.2			8.0	3.0		4	9,10,38
14	1715 08 22		(18.5	70.3)	7.5					3	31,51
25	1836 07 03	2230	22.5	70.3	7.5		2.0	1.0	1.0	3	52
37	*<1868 08 13	2045	18.6	71.0	8.5		21.0	4.3		4	52
43	1869 06 25		(19.6	70.2)			0.7		0.0		9,38
46	*1869 08 24	1710	18.6	70.0	6.8		2.0	1.0		4	52
49	1871 10 05	0050	20.1	71.3	7.5						9,38,51
51	1873 11 19		(23.6	70.4)			2.8		2.0		9,38
52	*<1877 05 10	0216	19.6	70.2	8.3		24.0	4.5		4	52
53	1877 05 15						0.7		0.0		9,38
54	1877 08 23		(20.2	70.1)			1.0		0.5	3	9,38
56	1878 03 12		(20.2	70.1)			0.7		0.0		9,38
57	1878 06 12		(23.6	70.4)			0.7		0.0		9,38
58	1881 07 14		(20.2	70.1)			1.4		1.0	3	9,38
59	1881 10 27		(19.6	70.2)			0.7		0.0		9,38
61	1882 09 14		(19.6	70.2)			0.7		0.0		9,38
62	1885 11 12	0740	(20.2	70.1)			1.0		0.5	3	9,38,51
63	1903 09 26		(20.2	70.1)			0.7	-0.5	0.0		9,38,51
65	1906 05 07		(18.5	70.3)			1.5	0.6	0.0		9,38
67	1906 12 26	0653	18.0	71.0	7.9	33					51
69	1909 06 08	0546	25.0	73.0	7.6	33					9,10,13,51
70	1911 09 15		20.0	72.0	7.3						51
76	*1918 12 04	1148	26.0	71.0	7.8	33	5.0	2.3	2.5	4	1,9,10,18,38,51
83	1923 08 12	1211	(18.5	70.3)			0.7	-0.5	0.0		9,38,51
84	1925 05 15	1157	26.0	71.5	7.1	50					51
89	1928 11 20	2035	22.5	70.5	7.1	33					51
93	1933 02 23	0809	20.0	71.0	7.6	40					9,22,38,51
94	1934 12 04	1725	19.5	69.5	6.9	130					9,22,38,51
95	1936 07 13	1112	24.5	70.0	7.3	60	1.0	0.0	0.5	4	1,9,10,22,51,52
99	1940 10 04	0755	22.0	71.0	7.3	75					51
103	1946 08 02	1919	26.5	70.5	7.9	60					51
105	1948 12 26	0712	22.5	69.0	7.0		0.7	-0.5	0.0	3	9,38,51
115	1956 01 08	2054	19.0	70.5	7.1	55					51
116	1956 12 18	0231	25.5	71.0	7.0	33					51
117	1957 07 29	1715	23.5	71.5	7.0	33					51
125	1965 02 23	2211	25.7	70.5	7.0	80					51
129	1966 12 28	0818	25.5	70.6	7.8	32	0.4	0.0	0.5	4	5,9,38,47,51
132	1967 12 21	0225	21.7	70.0	7.5	33	0.7	-0.5	0.0	4	9,27,38,51
135	1970 06 19	1056	22.2	70.5	7.0	52					51
136	1970 11 28	1109	20.9	69.8	6.0	33					51
143	1975 03 13	1527	26.0	75.0	6.7						51
145	1983 10 04	1852	26.5	70.6	7.4	15	0.4	-2.3	0.2	4	45

NOTE: * indicates that the earthquake caused a destructive tsunami.
< indicates that the tsunami was reported outside the South American coast.
( ) Parentheses around the latitude and longitude indicate that the epicenter was derived from the coordinates of a city name given in the reference.

Table 2.3.1.- Major tsunamigenic earthquakes of northern Chile (from Lockridge 1985). See localisation Fig. 2.3.5.



TERREMOTO DE IQUIQUE 1868

TERREMOTO DE ARICA 1877

Fig. 2.3.6.- Rupture surface of the 1868 and 1877 earthquakes, according Kausel (1986) (from Kausel & Campos, 1992).

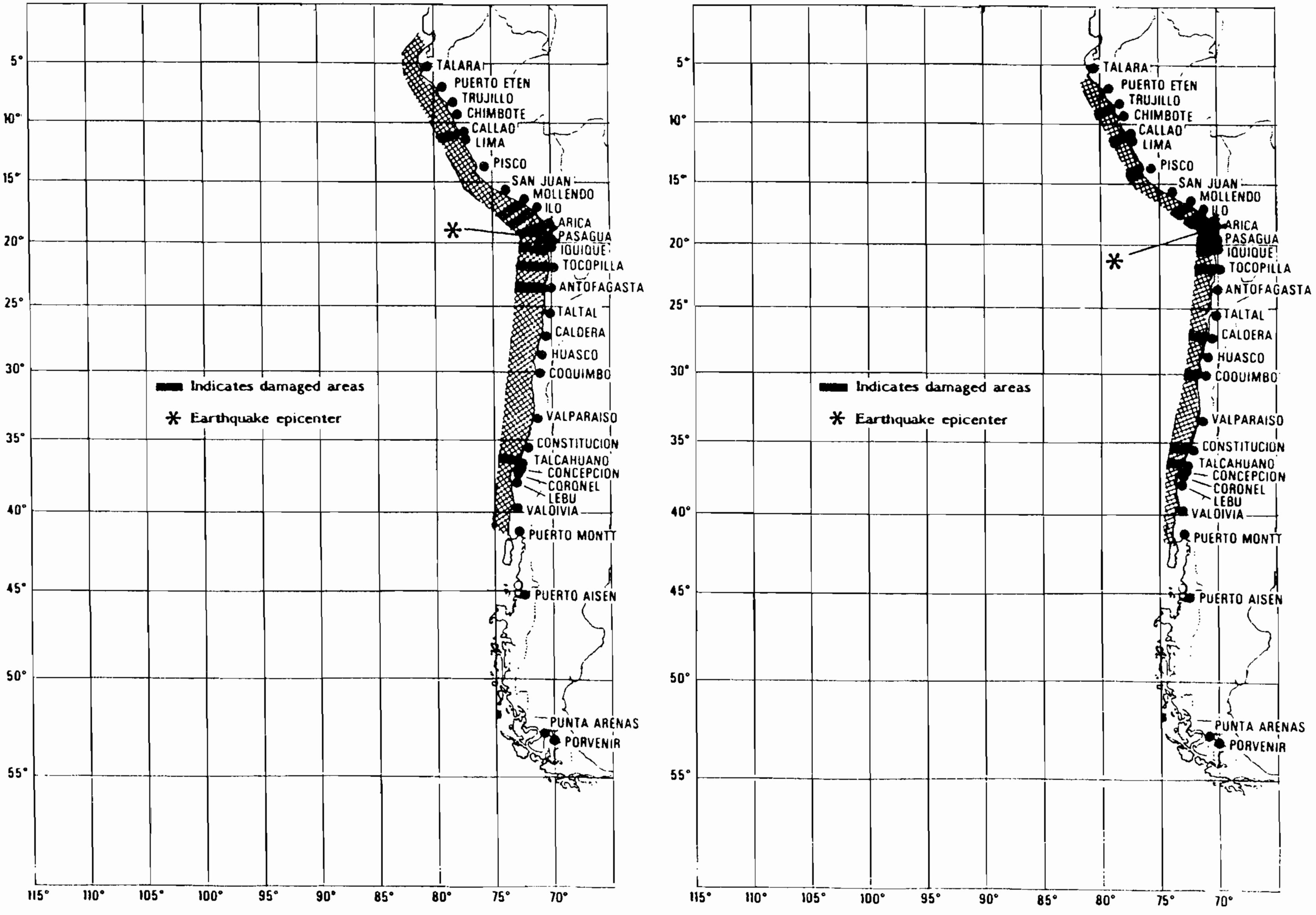


Fig. 2.3.7.- Areas affected by the 1868 and 1877 tsunamis in Peru and Chile (from Lockridge 1985).

EVENT DATE YEAR MO DA	REPORTING CITY OR REGION	EFFECTS	NO. OF DEATHS
1705 11 26	ARICA, CHILE	TOWN DESTROYED	
1868 08 13	ARICA, CHILE	MANY SHIPS DESTROYED	25,000
	CALDERA, CHILE	SHIPS DAMAGED	
	IQUIQUE, CHILE	CITY COMPLETELY SUBMERGED	150
	CORONEL, CONSTITUCION, COQUIMBO, BAJO, COBIJA, TOCOPILLA, TALCAHUANO MEJILLONES, PISAGUA, AND JUAN FERNANDEZ IS., CHILE	CONSIDERABLE DAMAGE	
	TOME, CHILE	WAREHOUSE, CUSTOM HOUSE FLOODED	
	TRUJILLO, PERU	SOME DAMAGE	
	ILO, PISCO, PERU	ALL WASHED AWAY	20
	CALLAO, PERU	CONSIDERABLE DAMAGE	
	TAMBO, PERU	SETTLEMENT WASHED AWAY	500
	MOLLENDO, PERU	SETTLEMENT, WAREHOUSES WASHED AWAY	
	HILO, HAWAII ISLAND	SEVERE DAMAGE	
	MAUI AND MOLOKAI ISLANDS	SOME DAMAGE	
	RAPA, AUSTRAL ISLANDS	SETTLEMENTS DESTROYED	
	ANTARCTICA	BREAKUP OF ICE FLOW	
	APIA, WESTERN SAMOA	CHURCH AND BRIDGE DESTROYED	
	PIGEON BAY AND LEBON BAY, NEW ZEALAND	SOME DAMAGE	
	YOKOHAMA, JAPAN	HARBOR FLOODED	
1869 08 24	ARICA, IQUIQUE, AND PISAGUA, CHILE	TOWNS FLOODED	
1877 05 10	ARICA, CHILE	LOSS OF SHIPS	277
	IQUIQUE, CHILE	CITY PARTIALLY FLOODED.	30
	IQUIQUE, CHILE	$1.6 MILLION IN DAMAGE	
	TALCAHUANO, CHILE	CONSIDERABLE DAMAGE	
	CALETA PABELLON DE PICA, CHILE	LOWER CITY COMPLETELY DESTROYED	40-200
	CHANABAYA, CHANARAL, CHILE	CITIES FLOODED	
	HUANILLOS, TOCOPILLA, COBIJA AND MEJILLONES, CHILE	CITIES MOSTLY DESTROYED	MANY
	ANTOFAGASTA AND, PENCO, CHILE	SOME DESTRUCTION	
	ILO, PERU	EXTENSIVE DAMAGE	
	CALLAO, PERU	SOME DESTRUCTION	HUNDREDS
	MOLLENDO, PERU	RAILWAY WASHED OUT	
	HILO, HAWAII ISLAND	57 HOUSES DESTROYED	5
	ACAPULCO, MEXICO	SOME DESTRUCTION	
	CHATHAM ISLANDS	BRIDGE AND HOMES WASHED AWAY	
	LE BON BAY, NEW ZEALAND	TWO BRIDGES DESTROYED	
	AKAROA, NEW ZEALAND	COASTAL HOMES FLOODED	
	OMARU, NEW ZEALAND	PIER DESTROYED	
	HAKODATE, JAPAN	PART OF CITY FLOODED	
1918 12 04	CALDERA, CHILE	SOME DAMAGE	

Table 2.3.2.- Damage and number of deaths provoked by tsunamis originated in north Chile, mainly in 1868 and 1877 (from Lockridge 1985).

Table 2.3.3.- Effects in Peru and Chile of the major tsunamis registered in northern Chile from Lockridge 1985).

EVENT DATE YEAR MO DA	COUNTRY	REPORTING CITY OR REGION	S. LAT. °	W. LONG. °	RUNUP (M)	DAMAGE
1615 09 16	CHILE	ARICA	18.48	70.33		
1705 11 26	CHILE	ARICA	18.48	70.33		X
1836 07 03	CHILE	COBIJA	22.55	70.27		
1868 08 13	PERU	TAMBO	7.58	78.70		X
	PERU	TRUJILLO	8.10	79.00		X
	PERU	CASMA	9.50	78.30	2.5	
	PERU	CALLAO	12.08	77.13	4.0	X
	PERU	CHINCHA ISLANDS	13.65	76.40		X
	PERU	PISCO	13.77	76.70		X
	PERU	CHALA	15.85	74.22	15.0	X
	PERU	MOLLENDO	17.00	72.00		X
	PERU	ISLAY	17.03	72.10	12.0	
	PERU	ILO	17.70	71.33		X
	CHILE	ARICA	18.48	70.33	15.0	X
	CHILE	PISAGUA	19.57	70.23		X
	CHILE	IQUIQUE	20.25	70.13	12.0	X
	CHILE	TOCOPILLA	22.08	70.17		X
	CHILE	COBIJA	22.55	70.25		X
	CHILE	MEJILLONES	23.05	70.42	6.0	X
	CHILE	TALTAL	25.43	70.55		
	CHILE	CHANARAL	26.38	70.67		X
	CHILE	CALDERA	27.07	70.83		X
	CHILE	CARRIZAL BAJO	28.13	71.25		X
	CHILE	COQUIMBO	29.95	71.42	7.5	X
	CHILE	JUAN FERNANDEZ ISLANDS	33.00	80.00	2.0	X
	CHILE	VALPARAISO	33.08	71.67		
	CHILE	SAN VINCENTE	34.45	71.08		
	CHILE	CONSTITUCION	35.33	72.42	3.5	X
	CHILE	TOME	36.63	72.95	4.5	X
	CHILE	TALCAHUANO	36.67	73.17	4.0	X
	CHILE	CORONEL	36.98	73.17		
	CHILE	LOTA	37.12	73.17		
	CHILE	ARAUCO	37.25	73.32		
	CHILE	LEBU	37.63	73.72		
	CHILE	SAN VINCENTE DE CANETE	37.80	73.42		X
	CHILE	CORRAL	39.86	73.42	4.0	
	CHILE	ANCUD	41.87	73.83		
	CHILE	CHILOE ISLAND	42.50	73.92		X
1869 08 24	CHILE	PISAGUA	19.57	70.23	2.0	X
	CHILE	IQUIQUE	20.25	70.13	2.0	X
	CHILE	ARICA	18.48	70.33	2.0	X
1877 05 10	CHILE	HUANILLOS			18.0	X
	PERU	TUMBES	3.62	80.45		
	PERU	PIMENTEL	6.85	79.88		
	PERU	PACASMAYO	7.45	79.55		
	PERU	TAMBO	7.58	78.70	4.0	
	PERU	HUANCHACO	8.05	78.10		X
	PERU	SALAVERRY	8.23	78.92	0.8	
	PERU	SANTA	8.95	78.62	3.0	
	PERU	CHIMBOTE	9.08	78.60	2.0	
	PERU	SAMANCO	9.22	78.55	3.5	
	PERU	CASMA	9.50	78.30	2.0	
	PERU	SUPE	10.82	77.67	6.0	
	PERU	MOLLENDO	17.00	72.00	3.0	X
	PERU	ISLAY	17.03	72.10	3.0	
	PERU	ILO	17.70	71.33	6.0	X
	CHILE	ARICA	18.48	70.33	20.0	X

1877 05 10	PERU	SALINAS (PTA)	11.33	78.50	6.0	
	PERU	ANCON	11.78	77.11	1.5	
	PERU	CALLAO	12.08	77.13	3.0	X
	PERU	CHINCHA ISLANDS	13.65	76.40	3.0	
	PERU	PISCO	13.77	76.70	3.0	
	PERU	CHALA	15.85	74.22	3.0	
1877 05 10	PERU	PISAGUA	19.57	70.23	5.0	
	CHILE	IQUIQUE	20.25	70.13	6.0	X
	CHILE	CHANABAYA	20.89	70.15	10.0	X
	CHILE	CALETA PABELLON DE PICA	20.90	70.16	10.0	X
	CHILE	PUNTA LOBOS	21.02	70.17	10.0	
	CHILE	GUANILLO DEL NORTE	21.20	70.08	15.0	
	CHILE	TOCOPILLA	22.08	70.17	24.0	X
	CHILE	COBIJA	22.55	70.27	9.0	X
	CHILE	MEJILLONES	23.08	70.43	21.0	X
	CHILE	ANTOFAGASTA	23.65	70.42	6.0	X
	CHILE	CHANARAL	26.38	70.67	5.0	X
	CHILE	CALDERA	27.07	70.83	2.0	
	CHILE	CARRIZAL BAJO	28.07	70.58	1.5	
	CHILE	COQUIMBO	29.95	71.42	2.0	
	CHILE	JUAN FERNANDEZ ISLANDS	33.00	80.00		
	CHILE	VALPARAISO	33.08	71.67	1.1	
	CHILE	LLICO	34.76	72.17		
	CHILE	CONSTITUCION	35.33	72.42	5.0	
	CHILE	TOME	36.63	72.95	0.8	
	CHILE	TALCAHUANO	36.67	73.17	15.0	X
	CHILE	PENCO	36.75	73.00		X
	CHILE	CORONEL	37.02	73.15	3.0	
	CHILE	LOTA	37.08	73.17	1.5	
	CHILE	ARAUCO	37.25	73.32		
	CHILE	VALDIVIA	39.77	73.25		
	CHILE	CORRAL BAY (ENSENADA)	39.96	73.42	0.6	
	CHILE	PUERTO MONTT	41.47	73.00		
	CHILE	ANCUD	41.87	73.83		
1877 08 23	CHILE	IQUIQUE	20.25	70.13		
1878 03 12	CHILE	BUCHUPUREO	36.08	72.77		
1878 06 12	CHILE	ANTOFAGASTA	23.65	70.42		
1881 07 14	CHILE	IQUIQUE	20.25	70.13		
1881 10 27	PERU	PISAGUA	19.57	70.23		
1882 09 14	PERU	PISAGUA	19.57	70.23		
1885 11 12	CHILE	IQUIQUE	20.25	70.13		
1903 09 26	CHILE	IQUIQUE	20.25	70.13		
1906 05 07	CHILE	ARICA	18.48	70.33		
	PERU	TACNA	18.00	70.25		
1918 12 04	CHILE	CALDERA	27.07	70.83	5.0	
1923 08 12	CHILE	ARICA	18.48	70.33		
1934 12 04	CHILE	ARICA	18.48	70.33		
1936 07 13	CHILE	ANTOFAGASTA	23.65	70.42		
	CHILE	TALTAL	25.43	70.55	0.8	
	CHILE	TALCAHUANO	36.67	73.17	1.0	
1948 12 26	CHILE	TOCOPILLA	22.08	70.17		
1966 12 28	PERU	CHIMBOTE	9.08	78.60	0.1	
	PERU	SAN JUAN	15.37	75.12	0.2	
	PERU	MATARANI	17.00	72.12	0.1	
	CHILE	ARICA	18.48	70.33	0.3	
	CHILE	ANTOFAGASTA	23.65	70.42	0.4	
	CHILE	CALDERA	27.07	70.88	0.4	

successive waves followed, each reaching a lower elevation than the previous one. The witnesses stressed that the inflow of the first wave corresponded to a silent swallowing phenomenon of the sea, not a violent wave. 97 houses were destroyed by the earthquake and the tsunami. Fourteen (or 44, according to other sources) deaths were mentioned. One may also mention that, coincidentally (?), an exceptional rainfall occurred at Cobija on May 14-15, a few days after the seism. Many anecdotical sources on historical earthquakes in Peru and Chile indicate a close relationship between unusual atmospheric phenomena (like heavy rains in the coastal desert, or anomalous thunderstorms) and seismic activity during the last four centuries.

At Stop 2.3, we shall observe the small mounts that remain from the former adobe walls of the houses built in the lower part of Cobija (Fig.2.3.8 and 2.3.9). Before 1877, part of the small city was built on the inner Holocene terrace, at the foot of the recently formed seacliff (below +5 to +7 m). This area which was completely destroyed by the wave, was never rebuilt. In a few places, among the ruins, a thin layer of coarse sand with shell hash and a few marine shells (mainly *Turritella cingulata*) was found. This deposit is generally covered with one or several layers of alluvial material. It is interpreted as a catastrophic coastal flooding, and it is inferred that it was deposited by the tsunami wave (although it might also be assigned to some violent storm, in the course of the last century).

Possible remnants of former tsunami in archaeological deposits.

Several metres above the *Aguada* Tres Palmas, a relatively thick sequence of archaeological remains have been accumulated in the last few thousand years. In the archaeological sequence of kitchen (shell and fish) remains, some beds with many small rounded pebbles and coastal sands are locally interstratified (Fig. 2.3.10). As these sedimentary units are made of sands and pebbles which compare well with those presently accumulated along the beach, it is hypothesized that they might have been brought atop the archaeological layers, not by man, but by natural processes. Thus, they might constitute remnants of tsunamis which would have reached a significantly higher elevation than the 1877 event.

The archaeological record at Cobija is supposed to encompass most of the Holocene (Bittman, 1978, 1980). The oldest occcupation may be correlated with the Huentelauquén culture, locally called « Pre-anzuelo de Concha Culture », and later with the « Anzuelo de Concha Culture » (7,000-4,000 BP). The following episode of occupation is characterized by the co-occurrence of shell and cactus hooks; it spanned the period 5,000-3,000 BP. The last prehistoric episode is the « Alfarera Phase » (with pottery) which ends during the Inca Empire. The historic period extends back to the XVIth century. More detailed data on the prehistorical and historical background of the area may be found in Bittmann (1980, 1984, Bittmann et al., 1980).

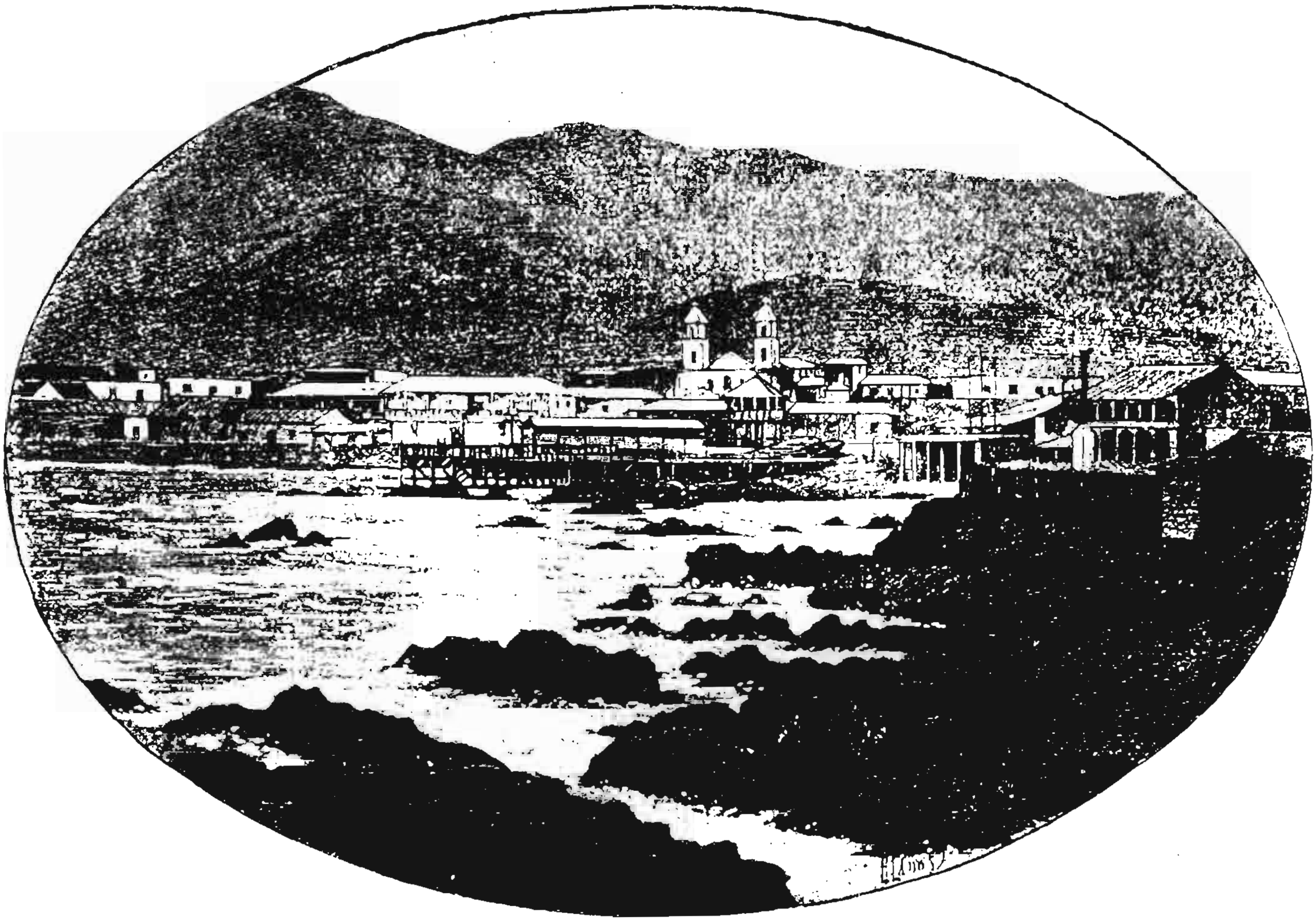


Fig. 2.3.8.- View of Cobija after the 1868 earthquake, and before the 1877 eathquake and tsunami (graving from H. Lanos, Bresson).

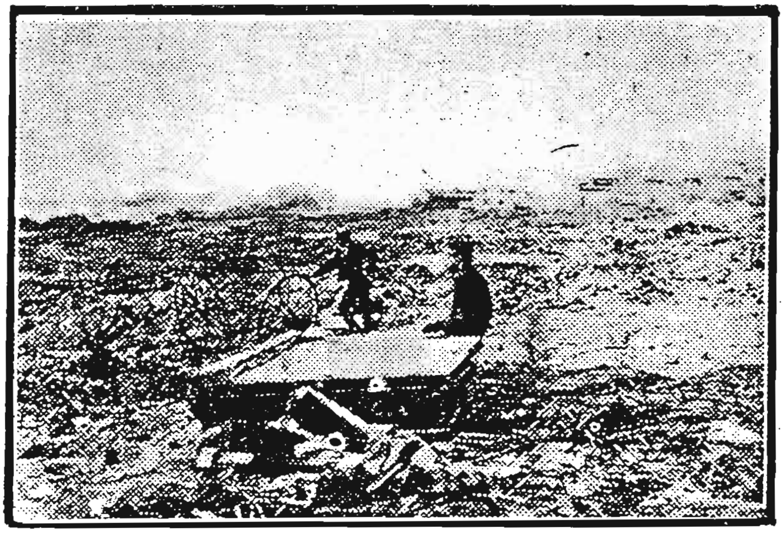


Fig. 2.3.9.- A photograph of the ruins of the lower part of Cobija, a short time after the 1877 tsunami (from Arce, 1930).

Fig. 2.3.10.- Natural cut in archaeological shell mound, showing an interstratified layer of small marine pebbles and coastal sands, which might indicate the trace of a former tsunami event. (Photo L. O.).

ALLUVIAL FANS IN THE GATICO AREA

Flint et al. (1991) divided the alluvial fans of the coast of northern Chile (Fig. 2.0.3) into three main groups on the basis of catchment size

- external fans, the largest ones, which have access to external drainage from within (or right through) the Coastal Cordillera;
- internal fans, which have a smaller catchment area in the western part of the Coastal Cordillera;
- and side cones, which correspond to scree deposits, generally without feeder canyon.

The external and internal fans may present one major channel, several large channels, or no dominant channel (only a system of smaller ones). The side cones often show trenching in the upper fan or gullying in the middle to upper fan area. It is not uncommon to observe steep side cones with maximum angle of 30°, while the external or internal fans exhibit slopes of the order of 10° in their middle part, and 2° in the lower part, near the toe.

At Gatico, the large alluvial fan (6 km wide) is of the external type but also includes small side cones (Flint et al., 1991) (Fig. 2.0.4). A set of secondary fans is found on the backshore: they have been fed by channels which eroded the toe of the major fan. The major part of the fan can be viewed as presently inactive, since nowadays the entrenched channels are concentrating most of the erosional/sedimentation activity: the entrenchment and the transport of alluvial material along the channels do not presently modifiy the fan surface.

Along the road south and north of Tocopilla, numerous examples of recent mud flows will be seen (Fig. 2.0.5). The 1991 rainstorm produced a series of mud- and alluvial flows; they are easily identified, in many cases, by a scanty vegetation (Fig. 2.0.6). The recurrence of this type of deposit is, at least for the XXth century, of the order of 3 or 4 events per 100 y (Ortlieb, 1996).

Another type of sedimentary deposit typical of the arid zones that can be observed along the coastal sector, north of Tocopilla are the thick, loosely consolidated, accumulations of scree on the flanks of steep ranges (Fig. 2.0.7).

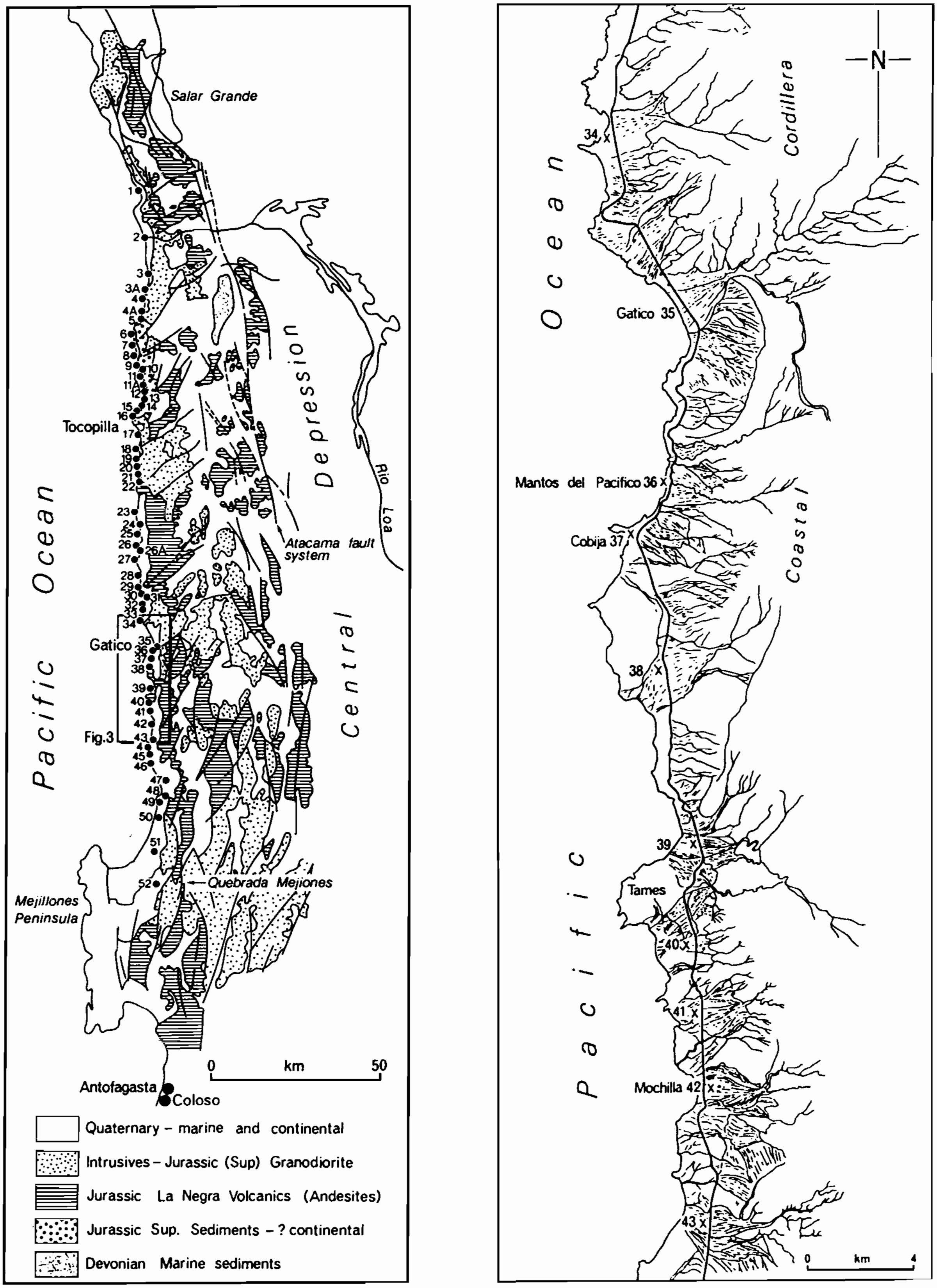
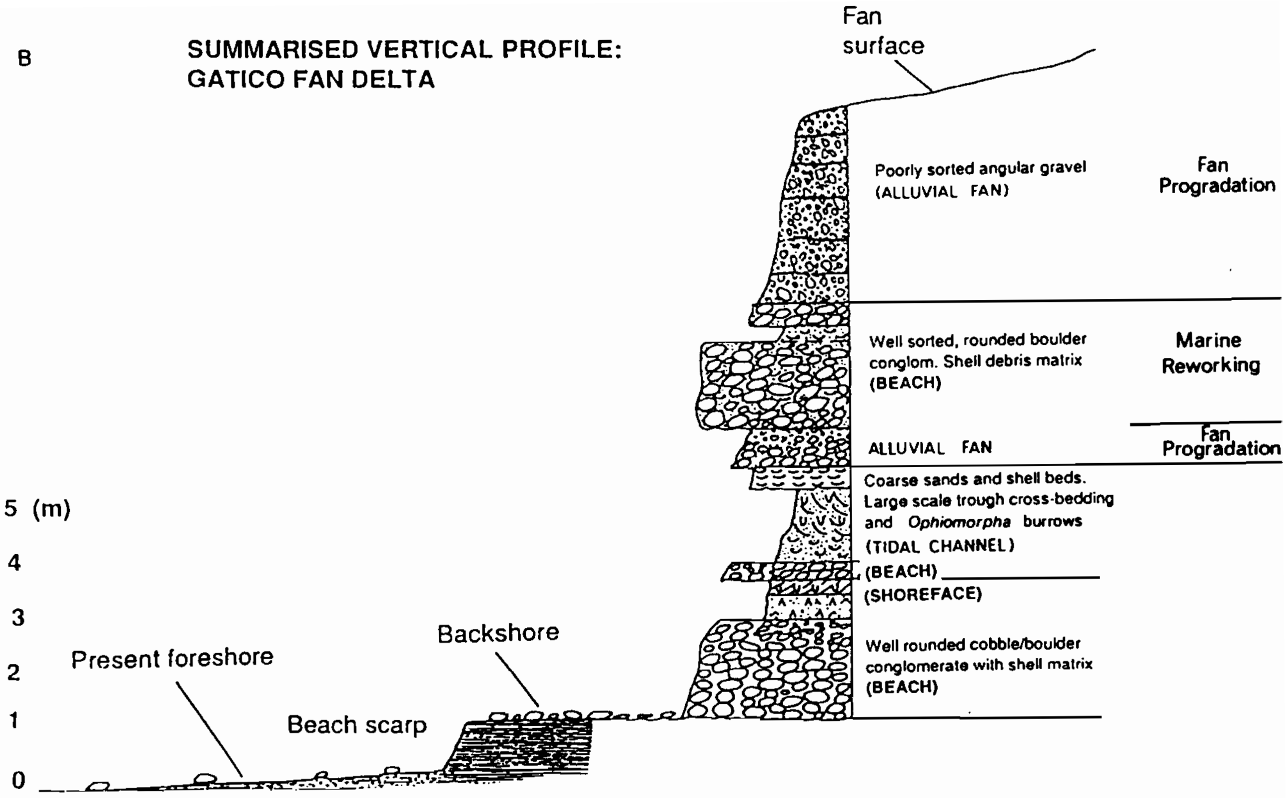


Fig. 2.0.3.- Alluvial fan systems between Mejillones Bay and the mouth of Rio Loa, with details studied by Flint et al. (1991) in the area of Michilla-Gatico.



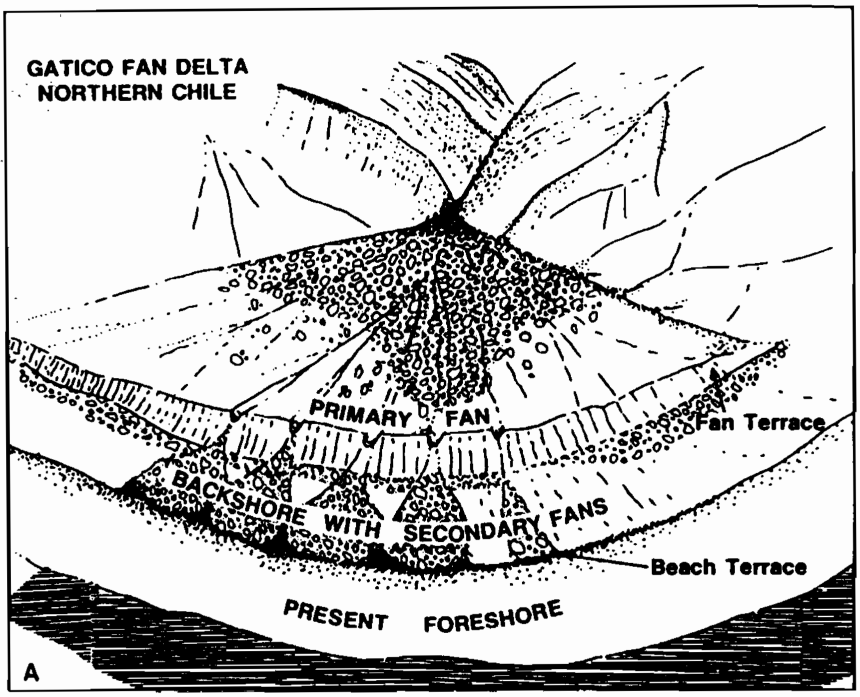


Fig. 2.0.4.- The Gatico fan delta: A- depositional and erosional environments; B- summary log of the associations and interbedding of subaerial and subaqueous deposits (from Flint et al., 1991)..

Fig. 2.0.5.- Recent alluvial deposits in road cuts at Gatico. The alluvial flows produced by exceptional storms are of limited width and several dm thick. (Photo L.O.).

Fig. 2.0.6.- Mud flow deposit resulting from the 1991 rain, north of Guanillos (22°S). Note the remnants of scarce vegetation which used the humidity preserved in the silty sediment. (Photo L.O.)

Fig. 2.0.7.- Steep slope deposits and scree, typical of areas with extreme aridity, 10 km N of Tocopilla. (Photo L.O.).

Fig. 2.0.8.- View of the Coastal Scarp near Tocopilla: in this sector the Cordillera de la Costa is less steep than more to the north but the coastal plain is reduced to a minimum.

GUANO DEPOSIT AT PUNTA BANDURRIA DEL NORTE

In the locality Punta Bandurria del Norte (also called Guanillos del Sur) we shall observe a deposit of fossil guano associated to a Middle Pleistocene marine terrace. The guano deposits may be found in distinct kinds of location and geomorphological environments. In this case, the biogenic deposit is described as of the allochtonous type, because part of the material has been transported from a higher original position.

The guano sediment contains a high proportion of bird and marine mamal bones. At Bandurria del Norte, the partially reworked guano has been mixed with sand or pebbles of marine origin (Fig. 2.4.1).

Guano, as a mineral resource

The guano is a nitrate and phosphate sedimentary deposit resulting from the accumulation and subsequent leaching of bird excrement and bones. It is a typical biogenic sediment of the arid coastal areas bordering oceanic waters rich in phytoplankton. In northern Chile and southern Peru, the guano has been exploited as a fertilizer, since the incaic times. During the XIXth century and at the beginning of the present century, intensive exploitation of this resource led to a serious reduction of the natural stocks.

The useful guano is the red guano (« *guano rojo* »), not the white, relatively fresh, guano (« *guano blanco* »). The first one is an older deposit than the white guano, and is the result of a more evolved diagenetic process. The progressive loss of organic matter and relative humidity is accompanied by an enrichment in phosphate and leaching of soluble ammoniacal and potassic compounds. Examples of the chemical composition of red guano from three localities of the north Chilean coast (Huanillos, Paquica and Punta de Lobos) are indicated in Table 2.4.1 (from Vila, 1953). According to the Chilean law, the red guano must contain more than 18% of fertilizing matter (P_2O_5 , N and K_2O).

The outcrops of red guano are of variable shape and thickness (Table 2.4.2). The red guano is most often found in protected small depressions, against the bedrock, and below colluvial or slope deposit cover. The mining of this resource in the « *guaneras* » requires the stripping-off of the sedimentary cover which protected the guano (Fig. 2.4.2).

The white, nitrogen-rich, guano, which can easily be seen on islets and rocky points along the coasts of northern Chile and Peru, has a stratified, cardboard-like, texture.

Descriptions of the *guaneras* of the northern coast of Chile and historical accounts on the exploitation of this important resource may be found: Torres (1863); Blese (1950), Vila (1953), Zolezzi (n.d.), and in the *Boletín de la Compañía Administradora del Guano* (published in Lima, Peru). It is reminded that the exploitation of the guano deposits was a matter so important in the second half of the XIXth century that it provoked the Pacific War between Chile, Peru and Bolivia. At the end of this war, the territory between the 23rd S parallel and Arica became Chilean.

Paleoceanographic and paleoclimatic significance of the guano deposits

The preservation of guano deposits along the coast of northern Chile and of Peru has been interpreted by many authors as an indication of the permanency of the arid conditions

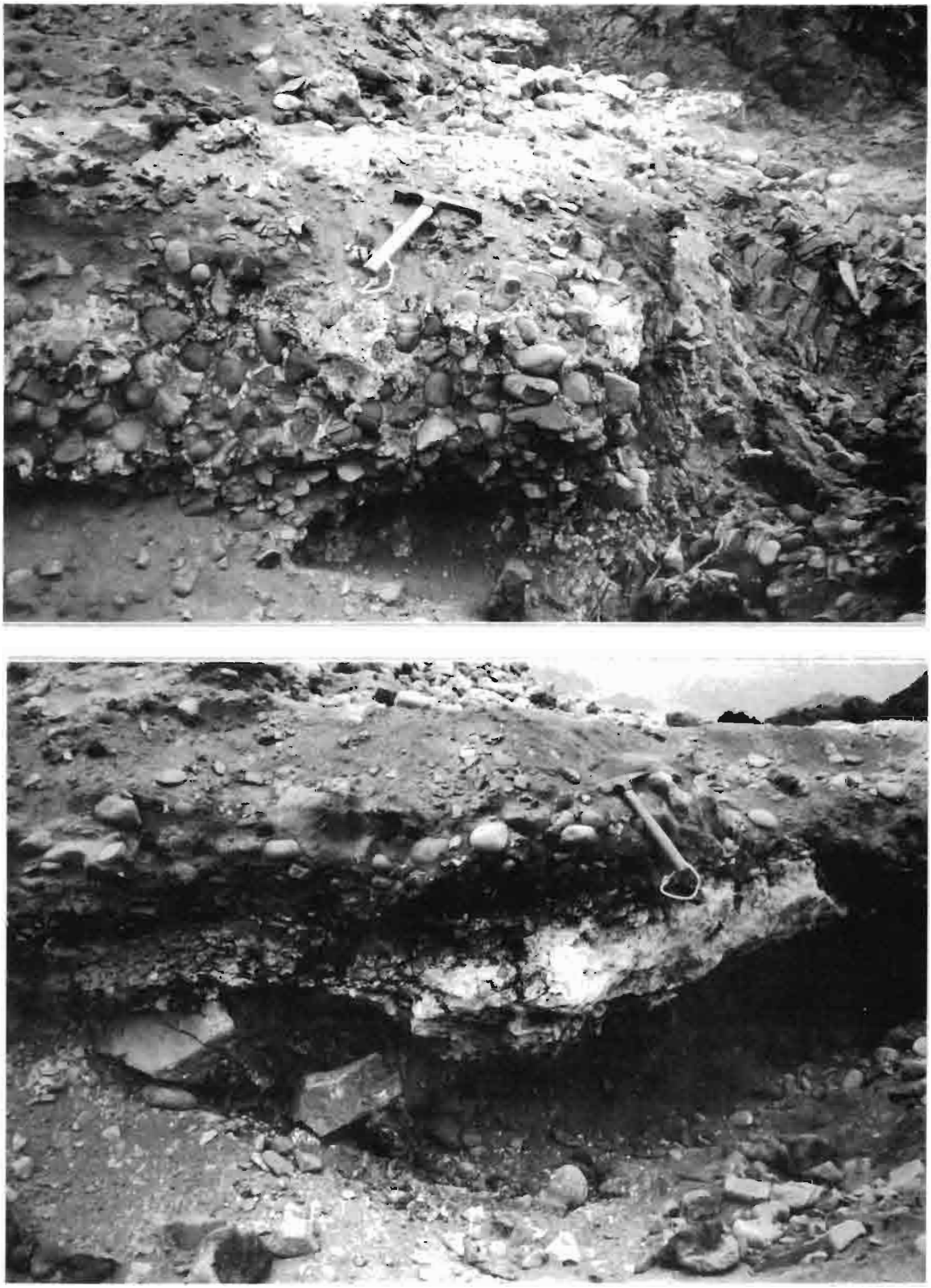


Fig. 2.4.1.- Guano deposit mixed with marine cobbles of a late Middle Pleistocene marine terrace, at Punta Bandurria del Norte (Photo L. O.).

Table 2.4.2 - ....(continued).

COVADERAS	Tipo Estratigráfico	Clasif. según import.	Distancia desde yac. anterior	Distancia entre los yacimient. grandes	Desembocadura del Río
			Kms.	Kms.	
Paso Malo	R.	1	3,5	51,5	
La Cachaza-Pta. Junín	R.	2	4,5		
Garrapata	R.	2	1,5		
Piojo	R.	2	2,5		
Punta Negra	R.	1	8		
Mejillones del Norte	R. (S.)	3	7		
Punta Ballena	R.	1	4		
Almacenes	R.	1	8,5		
Islotes Cololue	R.	1	2,5		
Viscacha	R.	1	5		
Kera	R. (S.)	3	4,5	40 Zona Sur 120 K.	
Punta Piedras	R.	1	12 (a)		
Punta Gruesa	S.	4	28		
Pozo Toyo	S.	3	7,5	17,5	
Cerro San Pedro	S.	1	7,5		
Chucumata	S.	3	2,5		
Patillos	R.	2	25,5	31,5	
Los Diques	S.	2	1,5		
Patache	S.	4	4,5		
Punta Negra	R.	2	8	10,5	
Chanavaya	S.	4	1		
Pabellón de Pica	S. (R.)	4	1,5	13	
Punta Lobos	S. (R.)	4	13	20	
Chomache	R.	2	12,5		
Guanillos del Norte	S. (R.)	4	7,5	17,5	
Punta Blanca	S. (R.)	3	4,5		
Chipana	S.	3	10	57,5	
3 kms. al Sur del Río Loa	R.	2	12		Loa
Andarivel Pta. Chilena	R.	1	3		
Punta Lautaro	S. (R.)	2	6		
Punta Colipí	S. (R.)	2	2,5		
Punta Arenas	R.	1	6,5		
Paquica	S. (R.)	3	27,5	83,5	
Guanillitos	R.	2	7,5		
Punta Atalá	S. (R.)	2	35,5		
Guanillos del Sur	S. (R.)	1	14,5		
Cobija	S. (R.)	3	16		
Hornitos	S. (R.)	1	40		
PENÍNSULA MEJILLONES					
Punta Angamos	R. (S.)	2	10,5		
Caleta Cuartel	R.(S.)	2	5		
Caleta Roble	R. (S.)	2	1,5		
Las Tetas	F.	3	1,5 (b)		
Oreja de Mar	R. (S.)	2	4		
Morro Mejillones	F.	4	1,5		
Isla Lagarto	R.	2	29		
Isla Santa María	R.	2	9		
La Portada	R.	2			

4 = Importante; 3 = Regular; 2 = Inferior; 1 = Sin importancia.

(a) Punta Piedras hasta Isla Iquique 6 kms.

(b) Desde Punta Angamos.

Table 2.4.1.- Chemical analysis of « red guano » from three localities of the coast of northern Chile, where this resource has been actively exploited for more than a century (from Vila, 1953).

	Huanillos	*Paquica*	*Punta de Lobos*
Anhidrido fosfórico total	21,58%	19,33%	21,85%
Humedad	4,64%	3,47%	5,61%
Sílice e insolubles	29,48%	39,63%	27,80%
Materia orgánica. Agua de combinación y anhidrido carbónico	5,36%	5,11%	11,98%
Anhidrido sulfúrico	10,15%	11,10%	9,75%
Oxido de fierro y aluminio	2,10%	0,88%	0,73%
Oxido de magnesia	1,94%	1,35%	0,69%
Alcalis	1,80%	0,90%	1,20%
Oxido de calcio	22,42%	18,05%	20,18%
Cloruros (como NaCl)	0,70%	0,05%	0,20%
Nitratos (como $NaNO_3$)	0,35%	0,10%	0,10%

Table 2.4.2.- Distribution of the major *guaneras* in northern Chile, with indication of their geomorphological type and their economic importance (from Biese, 1950). R means « recent », S = subfossil, and F = Fossil guano.

COVADERAS	Tipo Estratigráfico	Clasif. según import.	Distancia desde yac. anterior	Distancia entre los yacimient. grandes		Desembocadura del Río
			Kms.	Kms.		
Isla Alacrán	R.	4			Zona Norte 52 K.	Azapa
La Capilla	R.	1	5	18		
Corazón	R.	2	1,5			
Roncador	R.	1	1,5			
Las Paradas	R.	2	1,5			
Pta. Vernal-Rda. Víctor	R. (S.)	2	7			
Camaraca	R.	3	1,5			
Pancho	R.	1	4,5	16		
Pta. Vítor	R.	1	7			Vítor
Ceciliana-C. Condell	R.	2	1			
Cabo Lobos	R.	3	3,5			
Pta. 8 kms. N. de Pta. Madrid	R.	2	18	88		
Punta Madrid	R.	2	8			
Islote 4 kms. al N. Camarones	R.	1	11			Camarones
Pta. 2 kms. al S. Camarones	R.	2	8			
Punta Gorda	R.	2	9,5			
Caleta Chica	R.	1	2,5			
Caleta Pisagua	R.	1	22,5			
Pichalo	S. (R.)	4	8,5			Tana

Fig. 2.4.2.- The *guanera* of Punta Lobos (21° S). Mining of red guano implies in many cases that the colluvial sediments accumulated at the foot of coastal hills be removed. The guano was concentrated, in different ways, upon the bedrock and below a sedimentary cover. (Photo L.O.).

of this coastal region during Quaternary times (Brüggen,1939; Kubler, 1948; Biese, 1950; Hutchinson, 1950; Schweigger, 1959, 1964; Craig, 1982). Among the hypotheses and interpretations proposed by these authors may be mentioned the following ideas:

- if the guano, normally accumulated in exposed areas, had not been dissolved, it meant that no rainy period had occurred for a long period of time;
- the guano deposits were accumulated in periods of the order of the whole Quaternary;
- the red guano might be of Pliocene age;
- the existence of guano deposits implies particular oceanographic conditions (because of the trophic chain involved) which should be coeval with arid conditions on land.

Ortlieb (1994, 1996) discussed these arguments and concluded that the last point above-mentioned is probably the most relevant and should be further studied. The Pliocene age formerly assigned to the red guano (mainly on the basis of the present elevation of the guano deposits on Morro de Mejillones, Brüggen, 1939) is considered as purely hypothetical. The red guano is a product of leaching processes which could not have occurred without a minimum of rainfall. Finally, the red guano is not found in exposed areas, but on the contrary is necessarily a buried sediment (Fig. 2.4.2).

The use of guano deposits in paleoceanographic research, for instance through biogeochemical studies of long sedimentary columns, is hampered by the scarcity of unexploited outcrops, and by the difficulty to obtain reliable geochronological controls.

EN ROUTE TOWARD IQUIQUE

From the last Stop, at Punta Bandurria del Norte, to Iquique, we shall travel for 300 km, following the foot of the Coastal Scarp (Fig. 2.0.8). The coastal plain will be of varying width. In some places several Pleistocene marine terraces can be distinguished at elevations generally inferior to +100 m. In other sectors, the Coastal Scarp plunges directly into the Pacific Ocean.

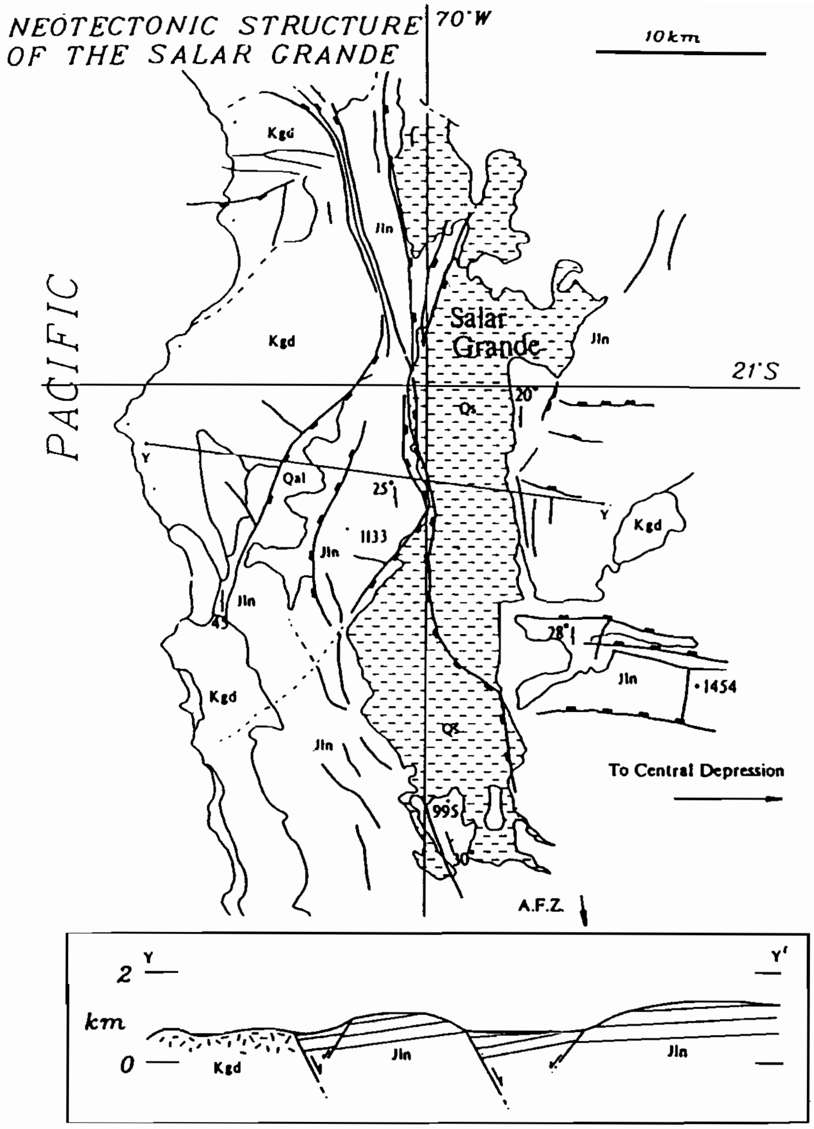
Along the road, particularly north of Tocopilla, many more evidences of mud flows that occurred in 1991 will be seen. We shall also see a series of *guaneras*.

When crossing the rio Loa, we shall enter the first Region of Chile. The rio Loa is the only permanent river of northern Chile, and largest river of the country. We shall comment the formation of the steep canyon of rio Loa, on our wayback to Antofagasta, at looking from the bus at the remnants of the paleo-lake Soledad.

The Salar Grande

A brief mention should be made on a locality with interesting neotectonic features but which is too far away from the coastal road to be visited by our party: the Salar Grande that is cut by an active fault of the Atacama Fault system (Fig.2.0.9). The Salar Grande is an intramontane tectonic basin within the Cordillera de la Costa (21°S), and at a short distance (but difficult access) from the main western escarpment. This salar is 35 km long and 15 km wide, and is supposed to be the largest deposit of halite in the world. It may be stressed that this huge stock of halite (99 % purity) is not of marine origin. It resulted from the evaporation of hyper concentrated brines that derived from a series of other aalars between the Andean Cordillera and the Cordillera de la Costa. It began to form in the Pliocene but most of the salt was probably accumulated during the Quaternary (Fig. 2.0.10).

A NNW-SSE trending fault system cuts the salar and the bordering fans, from north to south. The fault scarp in the salar suggests some recent activity.



Geological map and cross-section of the Salar Grande. *Jln* = Jurassic La Negra Formation; *Kgd* = Cretaceous granodiorite; *Qal* = Quaternary alluvium; *QS* = Quaternary salt.

Fig. 2.0.9.- Geological sketch and cross section of the Salar Grande, showing the active fault that cuts the thick salt accumulation (from Buddin et al., 1993).

Fig. 2.0.10.- Aspect of the surface of Salar Grande: a layer of silt covers the very thick salt accumulation.

LATE QUATERNARY COASTAL CHANGES IN NORTHERN CHILE

Guidebook for a fieldtrip
(Antofagasta-Iquique, 23-25 november 1995)

organized during the 1995 Annual meeting of the
International Geological Correlation Program Project 367
(19-28 November, Antofagasta, Chile)

Third day of Fieldtrip

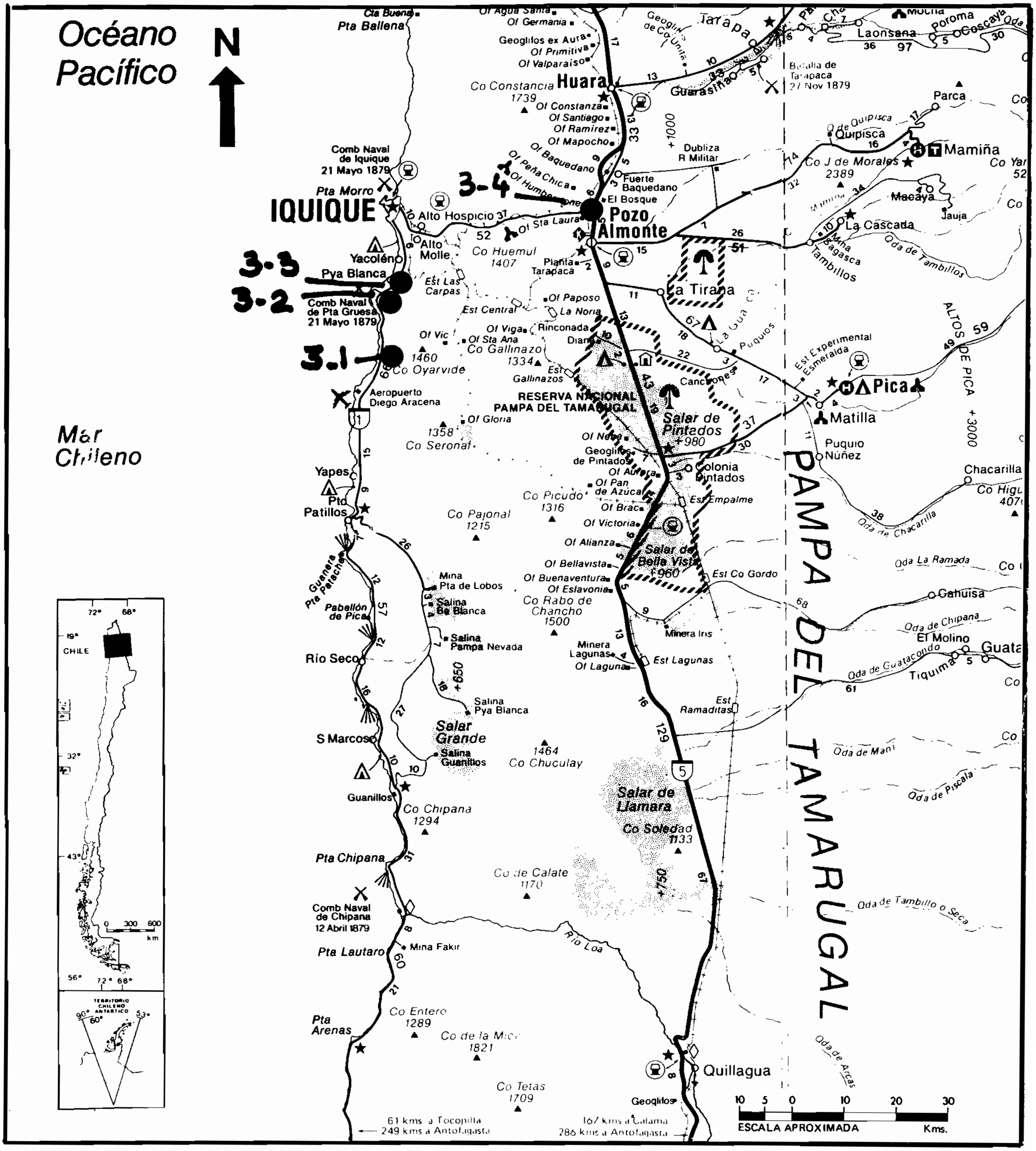


Fig. 3.0.1.- Localisation of the stops of the third day of the fieldtrip, near Iquique.

At Stop 3.1 (Fig. 3.0.1), we shall recall the different hypotheses relative to the formation of the Coastal Scarp and examine a couple of large landslides which were possibly produced by earthquakes.

THE COASTAL SCARP

Without contest, the Coastal Scarp is the major geomorphic feature of the northern coast of Chile (Fig. 3.1.1). The participants to the fieldtrip will have had the opportunity to see distinct aspects of this mega-seacliff (although they will not see the steepest and highest parts of this escarpment, which are found between Iquique and Arica, more to the north).

The evolution of the Coastal Scarp: several hypotheses.

In 1950, Brüggen interpreted that the Coastal Scarp was the product of a major fault structure which had uplifted the continental block of the Cordillera de la Costa (Fig. 3.1.2.). He denied that the feature was carved out by marine erosion. Later, Rutland (1971) considered that the fault scarp had been modified by coastal erosion. Then, in 1972, Mortimer, and Mortimer & Saric interpreted that the escarpment was of marine origin, and was formed during the Pliocene.

Paskoff (1976) viewed the escarpment as the remnant of a series of larger faulted scarps which were affected by retrograding erosion due to wave action (Fig. 3.1.2). This explanation accounts for the lack of fault lines along the Coastal Scarp. According to Paskoff (1976, 1978), the faulting activity would have been maximum at the end of the Miocene and in the early Pliocene. During the Middle Pliocene, a major transgression would have been responsible for a strong cliff erosion (able to produce several km of recession of the coastal scarp). Since then, the base of the cliff would have been abandoned by the sea.

Armijo & Thiele (1990) suggested that at least in the area of the Mejillones Peninsula, the Coastal Scarp represented a sligthly modified fault plane dipping toward the W. They considered the Cerro Moreno Fault (Fig. 1.2.6) as part of the Coastal Scarp fault system. This feature may be the superficial expression of a change in the dip of the subduction interface (at some 30 (?) km depth) (Fig. 3.1.3).

More recently, Hartley & Jolley (1995) stressed that, albeit the Cerro Moreno Fault (which they consider as not related to the Coastal Scarp), no indication of any Quaternary faulting is found along this major feature. They view the Coastal Scarp as a very old seacliff which is related to a Miocene uprising of the border of the continent.

LANDSLIDES FROM THE COASTAL SCARP AT PUNTA SARMENIA

North of Punta Sarmenia, a large landslide had been identified by Thomas (1970) (Fig. 3.1.4). A second landslide was observed at a short distance from the first one (Fig. 3.1.5). A photogeological analysis of the landslides shows that the northern one almost reached the present coastline and clearly postdates all the marine terraces preserved at the foot of the Coastal Scarp. The southern one covered a similar distance from its origin but occurred

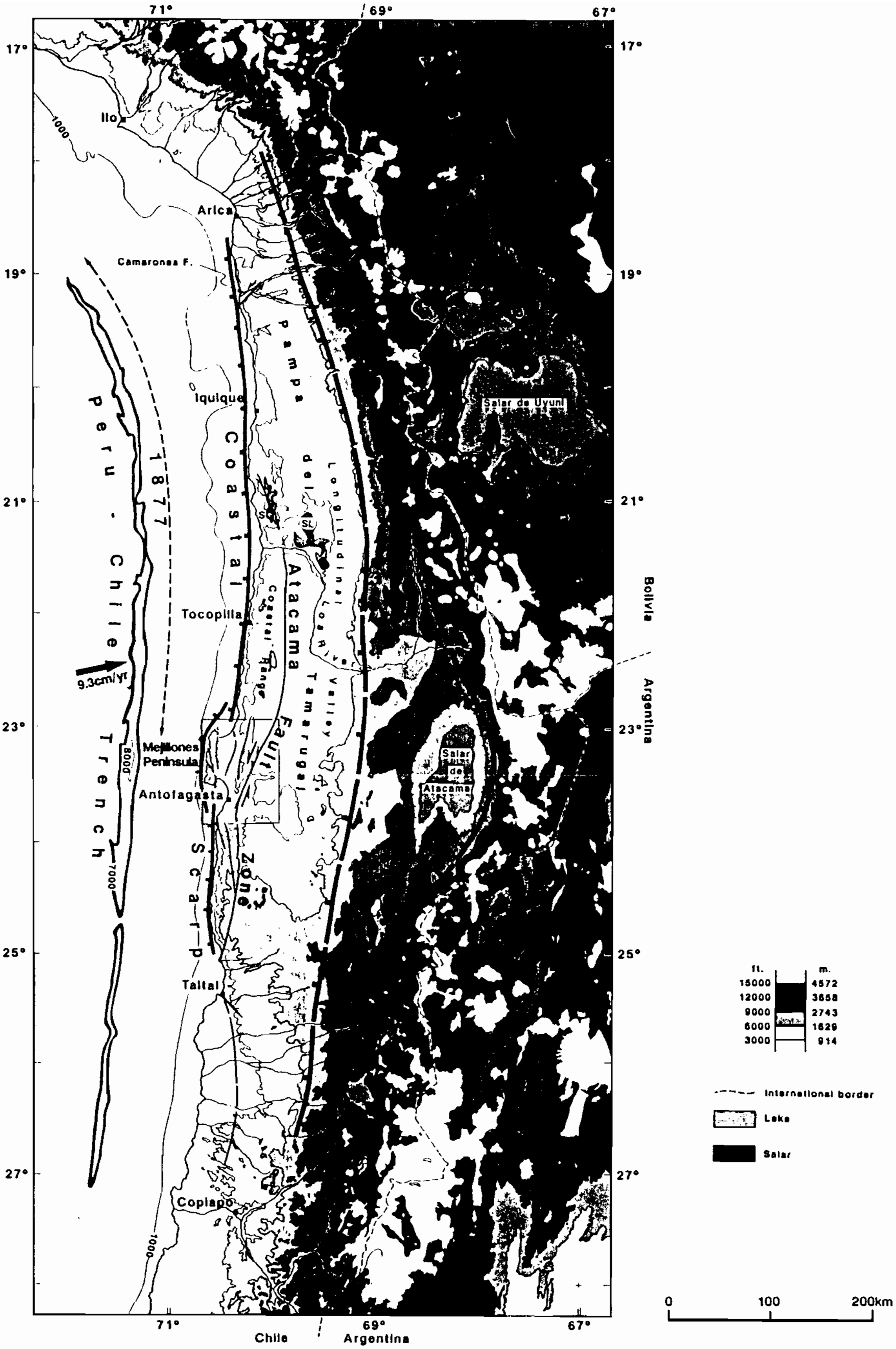
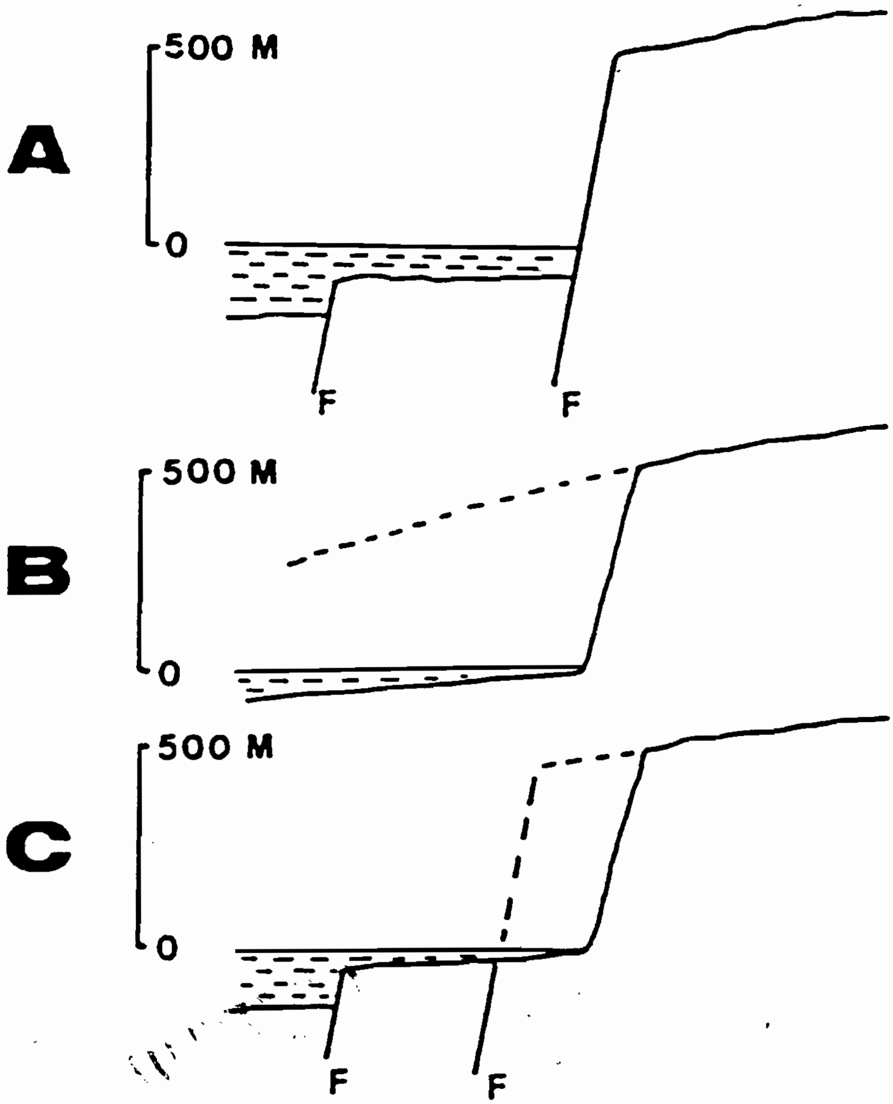


Fig. 3.1.1.- The Coastal Scarp in its structural framework, from Armijo & Thiele (1990).



Different hypothesis on the origin of the high sea cliff of northernmost Chile: A. according to BRÜGGEN (1950); B. according to MORTIMER and SARIČ (1972); according to PASKOFF (1976).

Fig. 3.1.2.- Principal hypotheses for the formation of the Coastal Scarp of northern Chile (see text) (from Paskoff, 1978).

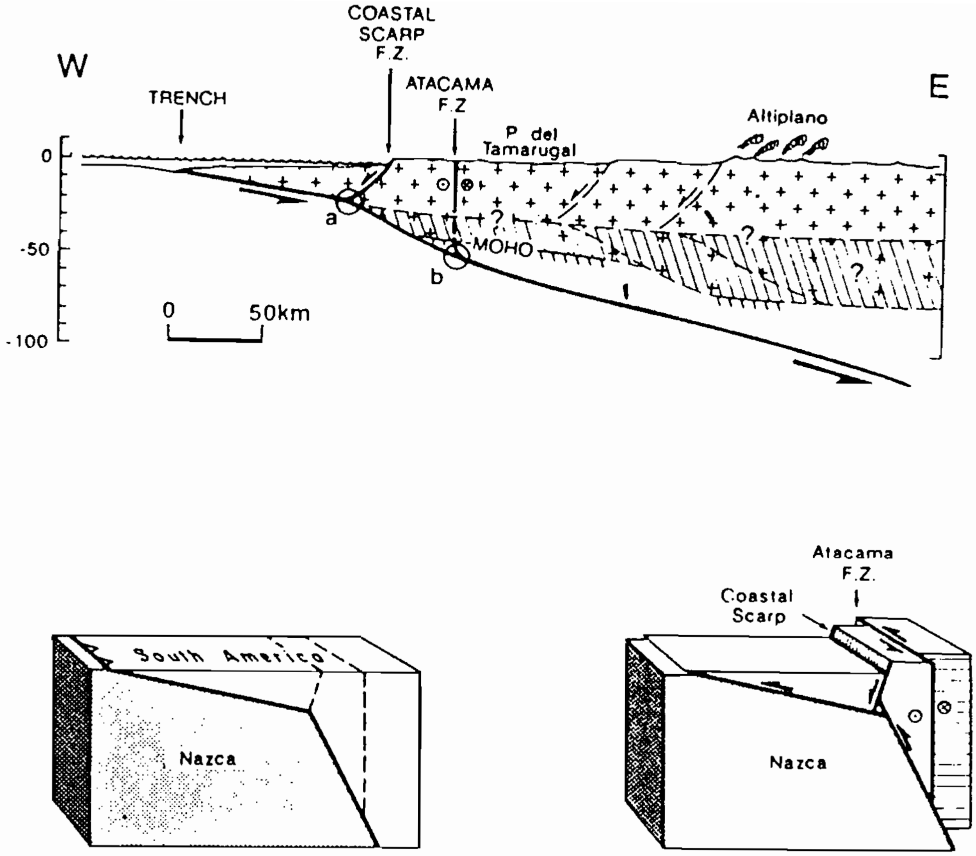


Fig. 3.1.3.- Idealized relationships between the Coastal Scarp and the Atacama Fault system, according to the model proposed by Armijo & Thiele (1990). Faulting at the Coastal Scarp would be linked to a subduction ramp, while the Atacama Fauklt Zone would absorb left-lateral slip.

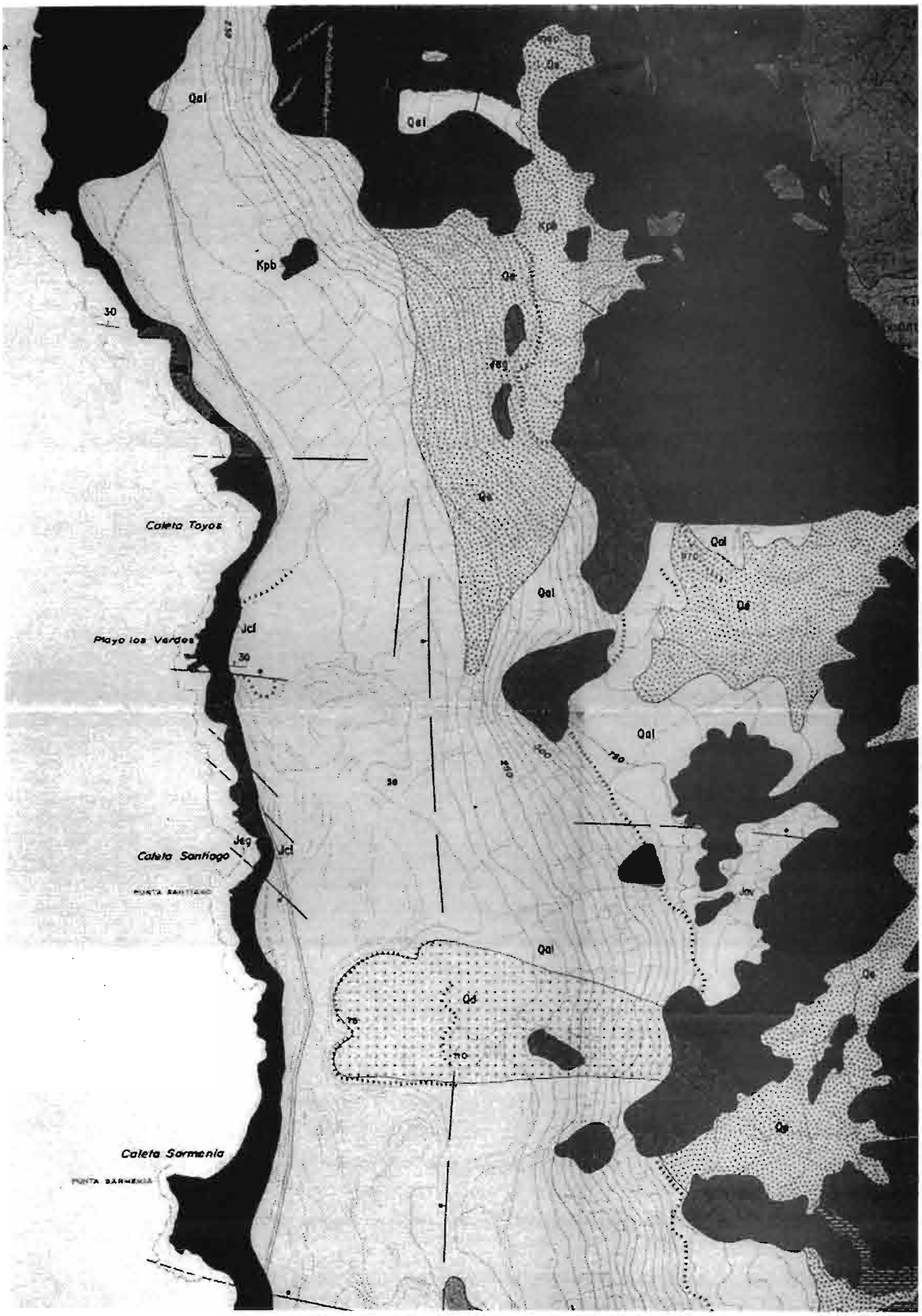


Fig. 3.1.4.- Fragment of the geological map (Caleta Molle Quadrangle, Tarapacá) showing only one of the two landslides (from Thomas, 1970).

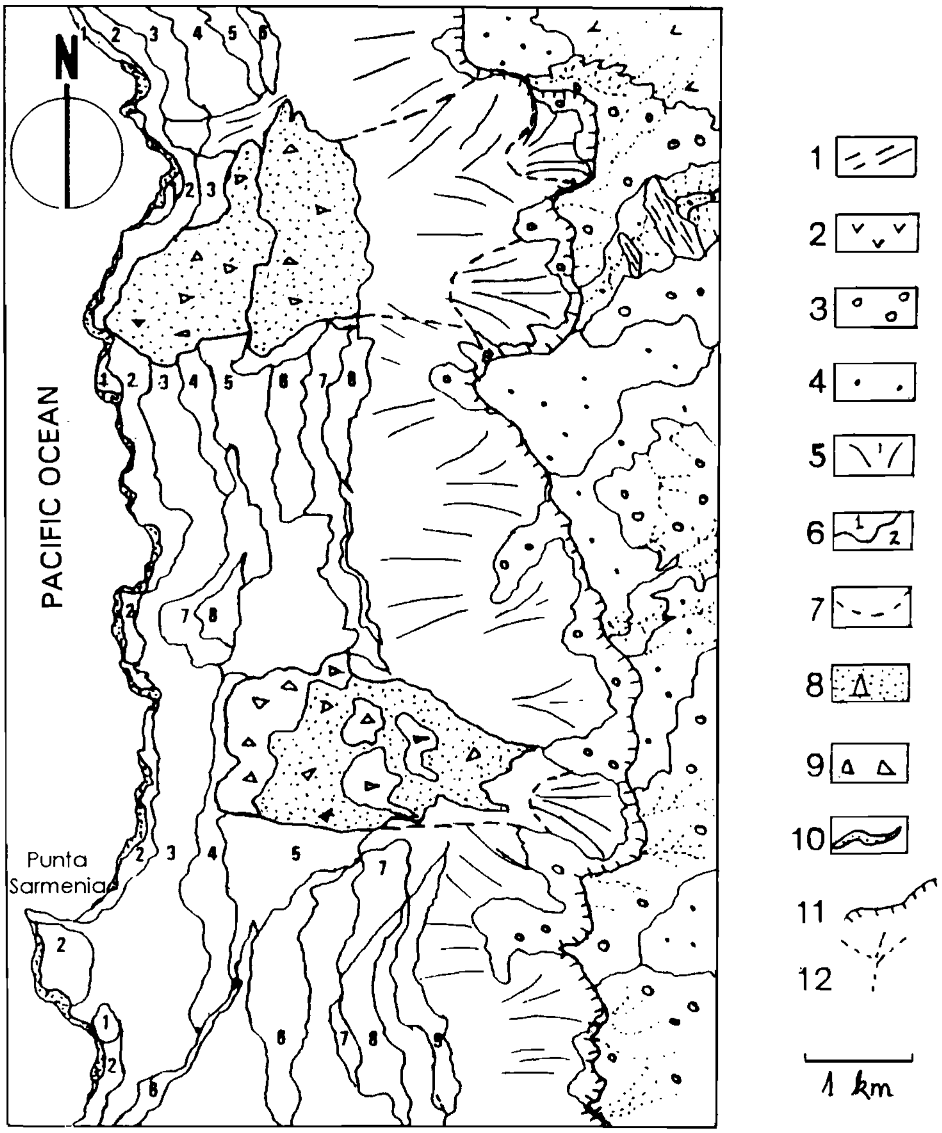


Fig. 3.1.5. Large landslides in the steep Coastal Scarp, near Punta Sarmenia (south of Iquique). These landslides may have been produced by seismic actvity.

1: Recent dunes; 2: Cretaceous volcanics and Seimentary rocks; 3: Jurassic sedimentary rocks; 4: Old alluvium; 5: Slope and eolian deposits; 6: Pleistocene marine platforms; 7: Landslide scar; 8: Landslide material; 9: Front of the landslide (coarser blocks); 10: Modern beach; 11: Coastal Scarp; 12: Hydrographic network.

in an area where the coastal plain is wider. Consequently, it stopped at a larger distance from the present shore, and only surmounted relatively older marine terraces. As both landslides display fairly well preserved scars, it is inferred that they are relatively young, probably Late Quaternary.

Landslides are commonly triggered by earthquakes, or violent runoff. On the coast of northern Chile, there is much more probability that former landslides were produced by strong seismic activity. In this respect, the proximity of the northern termination of the Atacama Fault Zone may not be fortuitous.

At Stop 3-2, Laurent Serrurier and David Lazo (Univ. Arturo Prat, Iquique) will present to the participants several aspects of the monitoring of present deformation and seismic activity in northern Chile. Hopefully, we shall have a demonstration of GPS measurement on one of the stations (Punta Gruesa) of the northern Chile network (Fig. 3.2.1). The setting up of this network began in 1991, in prevision of a possibly strong earthquake in the seismic gap of northern Chile. Remeasurement of the southern part of the network (Antofagasta) provided extremely valuable results for the quantification of the deformation linked to the July 30, 1995 earthquake (Ruegg et al., 1995).

A STUDY OF THE SEISMIC CYCLE IN NORTHERN CHILE

We include a short presentation prepared by colleagues of the Institut de Physique du Globe (Paris) and of the three Chilean institutions collaborating to this scientific program.

A study of the seismic cycle of Northern Chile

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Dept de Geofisica, Universidad de Chile, Santiago, Chile
J. Canuta, *Sernageomin, Santiago, Chile*
D. Lazo, L. Serrurier, *Universidad Arturo Prat, Iquique,Chile*
L. Ortlieb, *ORSTOM, Paris, France*

The historical records of seismicity along the North Chile and South Peru coastal areas (Dorbath et al., 1990; Comte and Pardo, 1991) indicate that two large earthquakes (m =8.5-9) ruptured the subduction interface between Nazca and South American plates at the end of last century (South Peru, 1868; North Chile 1877) corresponding to ruptures of about 400km. The 1868 earthquake covered approximately a zone between 16°S and 18°5S, while the 1877 earthquake extended from Arica (18°5S) to North Mejillones (23°S). Despite the lack of historical seismic information's due to the fact that this desertic region was nearly inhabited before 1850, we think that the recurrence time for such large subduction earthquakes is about 120 years. Northern Chile is thus a seismic gap in his mature phase. Most of the progress made in the understanding of the rupture process and source mechanisms within the seismic cycle have been obtained throught quantitative observations made in area of the world where large earthquakes occur frequently and particularly in the circum-Pacific subduction zones (Japan, California, Middle and South America). These observations reveal considerable spatial and temporal heterogeneities in the timing, initiation and recurrence of the earthquake rupture, but very few good observations are available about the pre-seismic stage of the seismic cycle. So quantitative near-field observations should bring relevant data (short and long term precursors) of the rupture iniation as well as about the time space distribution of the moment release.

Fig. 3.2.1.- GPS benches of the North Chile network set up in 1992: these were monitored in the weeks following the 1995 Antofagasta earthquake. Above, at Chacaya (S of Hornitos) ; below: a station SE of Antofagasta, on the road to La Escondida (Photos L.O.).

The North Chile seismic gap has been chosen as a target for a franco-chilean project for the study of the seismic cycle and forms a very good natural laboratory to obtain such data. The maturity of the gap and the high rate of plate convergence make the detection of precursors signals easier. The objective of the project, which has begun in 1991, is to monitor differents physical parameters (most of them in relation with crustal deformation) in relation with the preparation of a large earthquake in the North Chile seismic gap. This experiment includes a multiparameter observation site located at the center of the seismic gap near Iquique, a geodetic network a differents scales in the whole seismic area and geological investigations (field trips and satellite image interpretation). (Figure 1).

Multiparameter observation site.

To minimize the noise due to human activity, the site chosen is an abandoned mine in the hills near Iquique, power being supplied by a set of solar panels. The equipments installed are :

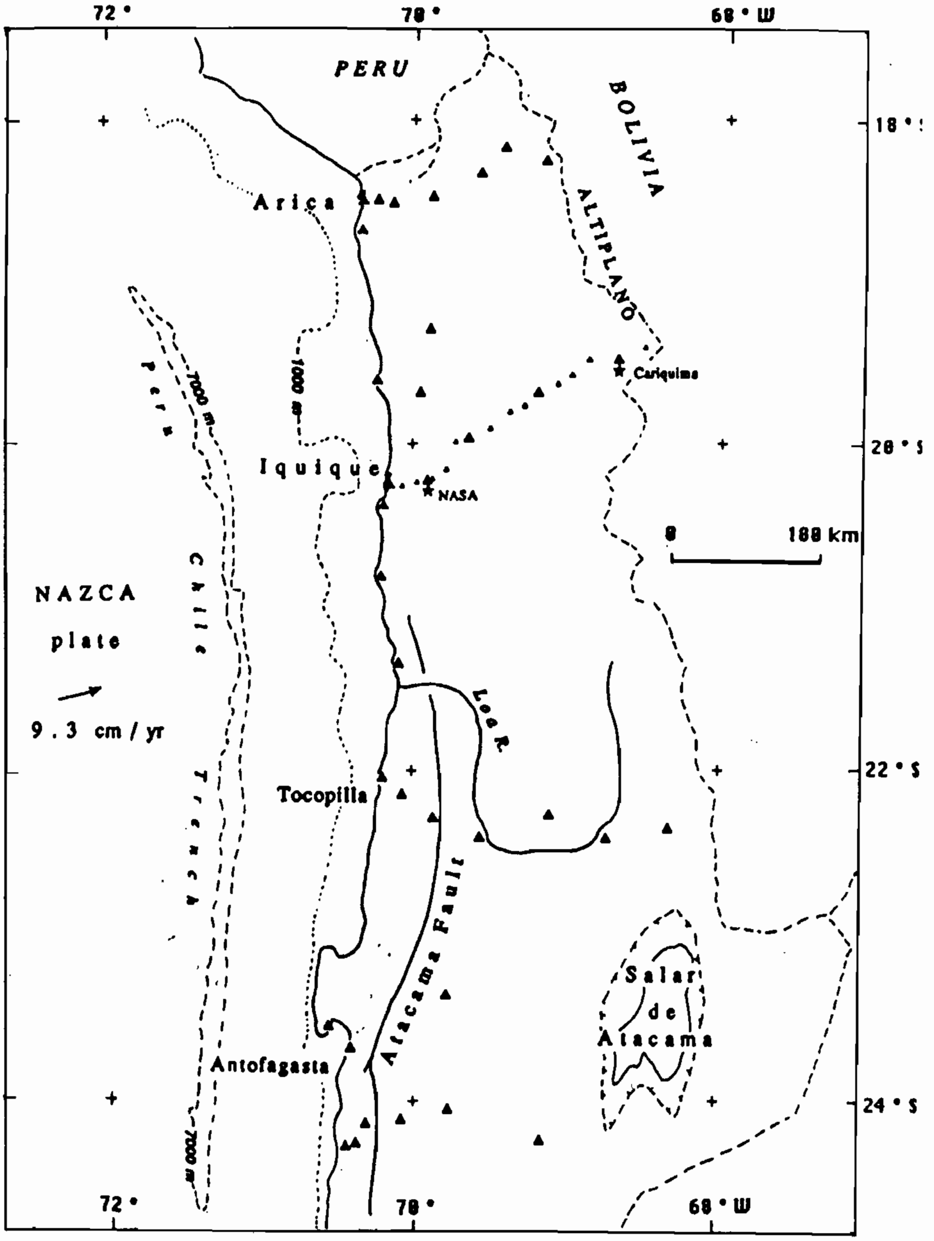
Tiltmeters : In many cases, it has been possible to observe rapid changes of the crustal deformation rate, in the months or the weeks preceding an earthquake; GPS surveys and tilt measuring are good ways to monitor such changes. Two types of tiltmeters are installed in the mine, 4 pendulums IPGP made and one water-tube designed by the Royal Observatory of Brussels. Theses tiltmeters record numerically ground inclination at the rate of one point per minute, in both geographical axes (E-W and N-S). Comparisons between records of differents intruments allow removing of parasites effects like terrestrial tide or seasonal variations.

VBB seismometer and accelerometer : In march of 1995, were installed a digital seismometer and accelerometer with wide frequency band and high dynamic range to monitor local seismicity. The seismometer records continuously and the accelerometer triggers on itself for events. Due to technical problems during the installation, we have few datas until now. In the future, seismological datas collected in Iquique will integrate seismological databases. Additionally, an analogic seismometer (smoked paper) records local seismicity level since 1993.

Gravimeter : A gravimeter, originally installed in the mine, then moved to Iquique due to his power consumption, records variations of the gravity field. The main effect is terrestrial tide, but it is possible to identify other effects which origin needs to be cleared.

GPS surveys

The zero epoch GPS campaigns were carried out in 1991 and 1992, with the installation of 4 East-West profiles in Arica, Iquique, Tocopilla and Domeyko (South of Antofagasta) and some coastal points installed with a mean distance of 50 km. This network, including 50 points covers a zone of 200 km wide from 18°5S to 23°5S and has been partially remeasured since the installation.
Besides, two Doris receivers are installed on the Iquique profile (figure 1) and give us a continuous recording of the distance between this two points. Soon after the $Mw = 8.1$ Antofagasta earthquake, that occurred on July, 30, 1995 two profiles were remeasured in Antofagasta and Iquique. Preliminary results show important relative displacement vectors on the Antofagasta profile with a maximum amplitude reaching 65 cm and an approximately East-West strike. Vertical displacement is



. Redes de geodesia espacial instalado en el marco del Proyecto "Estudio del ciclo sismico en Norte de Chile" por el consorcio de estudio franco-chileno. Triangulos chicos indican los puntos del perfil de Iquique (1991), los triangulos grandes los puntos medidos en 1992, y las estrellas las balizas DORIS.

Figure 1 : Location map of the geodetic spatial network installed in the Northern Chile seismic gap. Larges triangles figure principal points, while stars indicate the location of the Doris receivers.

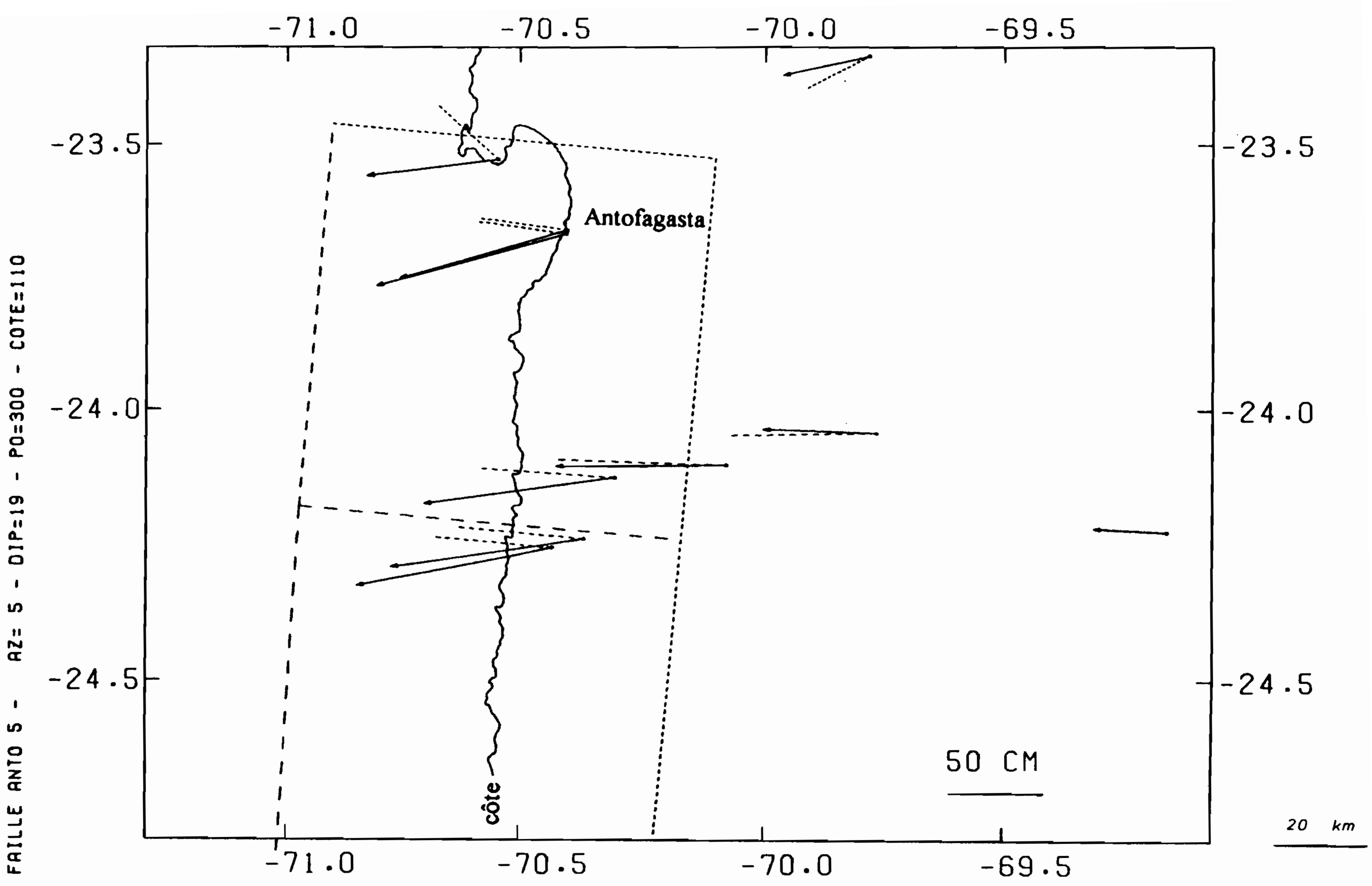


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Figure 2 : Observed (solid lines) and modelled (dashed lines) horizontal relative displacements for the July 30, 1995 Antofagasta earthquake. Observed displacement are the difference between relative coordinates of the GPS geodetic network mesured in November1992 and August 1995. The model used is a deep slip fault on the subduction plane with a 5 meters slip. Calculated magnitude for this model agrees with observed magnitude, the dashed frame is a surface projection of fault plane.

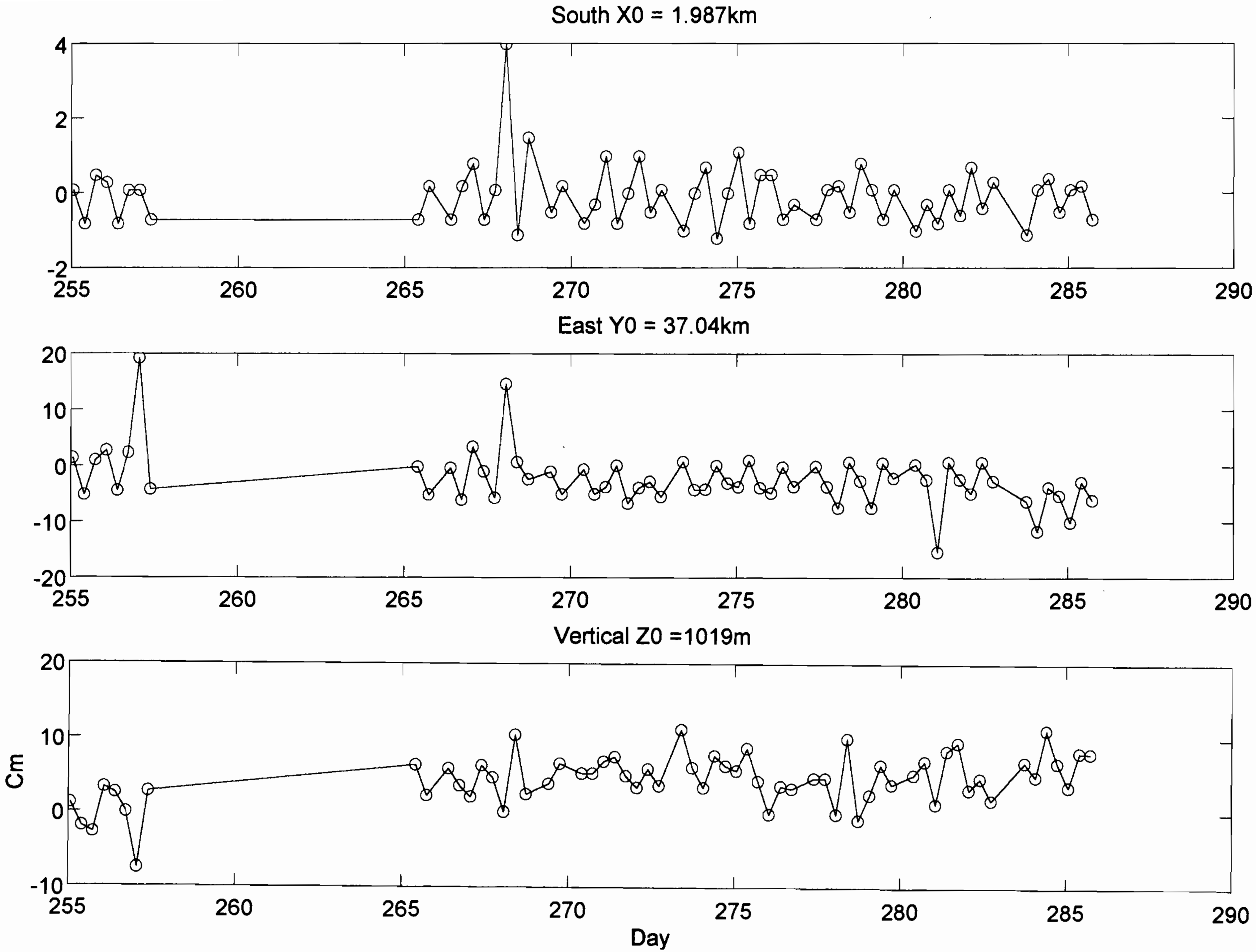

Figure 3.- Continuous GPS surveying. Plots of the elements of the Iquique-Pozo Almonte vector versus time. Only points with good confidence (rms <15 cm) have been kept

mostly a relative subsidence, between 0 and 40 cm, except for the northwestern point located to the south of the Mejillones peninsula, with relative uplift of about 15 cm. These results are in relative good agreement with the theoretical ones obtained with a dislocation model of a fault in an half space elastic medium (figure 2).

This earthquake has only ruptured the extreme south of the North Chile seismic gap, and, as shown by the microseismicity observed near Mejillones after the event, has deeply modified the stress repartition in the subduction interface. We thus decided to reinforce the experiment with a continuous GPS surveys between Iquique and Pozo Almonte installed in August 1995. Three sessions of 4 hours are recorded each day in Pozo Almonte, while in Iquique the recording is continuous to allow reattachment to the global IGS network (figure 3).

After the Antofagasta earthquake, a large subduction event in the Iquique seismic gap is still probable, and it is important to maintain surveillance of the area. Geodetic and geophysical datas collected in Iquique should bring interessant informations for the understanding of the seismic cycle.

References :

Armijo R., and Thiele R., Active faulting in Northern Chile : ramp stacking and lateral decoupling along a subduction plate boudary, *Earth Planet Sci. Lett., 98*, 40-61, 1990.

Comte D. and Pardo M. , Rappraisal of great historical earthquakes in the Northern Chile and Souther Peru seismic gaps, *Natural Hazards, 4,* 23-44, 1991.

Dorbath L., Cisternas A. and Dornath C., Quantitative assesment of great erathquakes in Peru, *Bull. Seism. Assoc. Amer., 80,* 551-576, 1990.

After Stop 3-2, we shall return toward Iquique. Several marine terraces will be observed between a few metres above MSL and about +130 m (Fig. 3.0.2). Some geochronological results were obtained a few years ago by Radtke (1989) on the sequence of terraces at the Golf Club (Playa Blanca) (Fig. 3.0.3).

STOP 3-3 HUAYQUIQUE

At Stop 3-3, is scheduled a brief presentation by colleagues of the Department of Marine Sciences, Univ. Arturo Prat, on the variability of the oceanographic conditions and on the manifestations of the El Niño anomaly, particularly with respect to the marine and terrestrial life, in northern Chile.

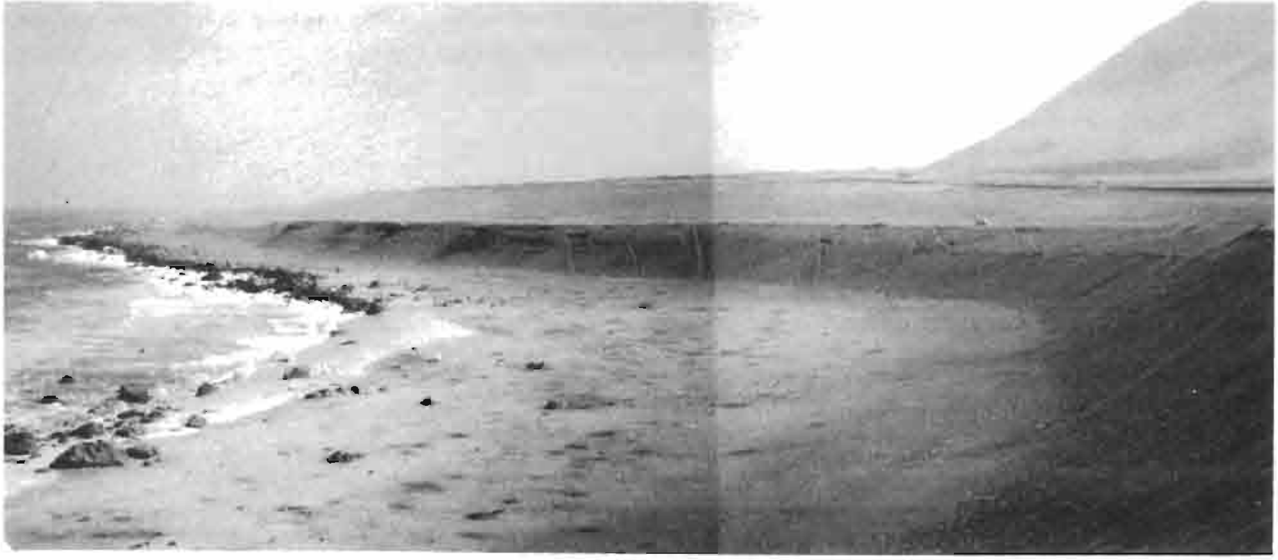

Fig. 3.0.2- Wide, composite marine terrace at the foot of the Coastal Scarp, south of Iquique (Punta Lobos). The palaeo-seacliff is 25 m high. (Photo L.O.).

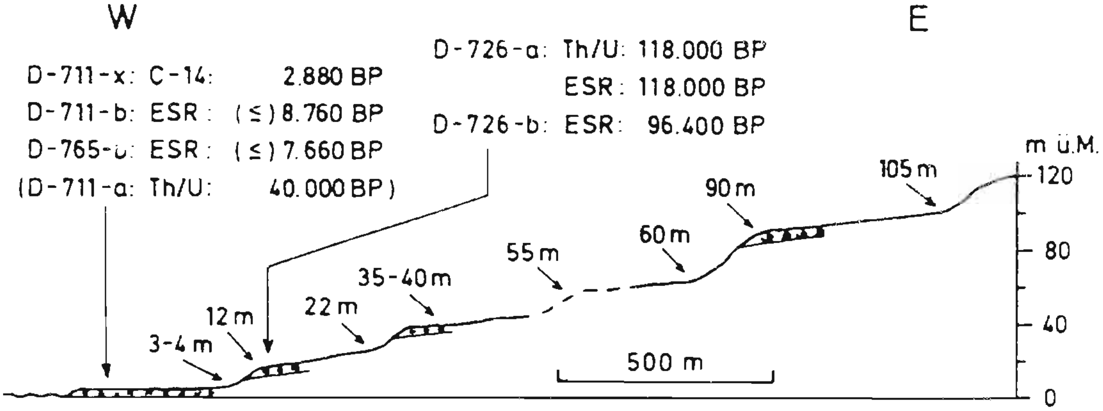

Fig. 3.0.3.- Series of marine terraces at the Gulf Club, South of Iquique, and geochronological (ESR and U/Th) results obtained by Radtke (1989).

Stop 3-4 will be dedicated to the « *salitre* » and the salitreras. The economic activity related to the salitre once was of major importance. The natural occurrence of salitre, and of other evaporitic minerals in the hyperarid Desert of Atacama have some paleoclimatic importance. The existence of some normally unstable and highly soluble evaporites, which have only be found in this exceptionally dry environment constitutes one of the strongest evidence for the durability of the aridity conditions during the Late Quaternary.

In Iquique, Guillermo Chong will present a general introduction to the geology and geomorphology of the salars (see distribution Fig. 3.4.1 & 3.4.2) and the nitrate occurrence. This talk should enable the participants to appreciate a series of geomorphic particularities of the Atacama Desert, during the (500 km-long) return to Antofagasta.

At Humberstone, Nelson Gallardo (Univ. Arturo Prat, Iquique) will present to the party a history of the exploitation of salitre in the last century. Enclosed is an abstract of his presentation ....

(see next page ......)

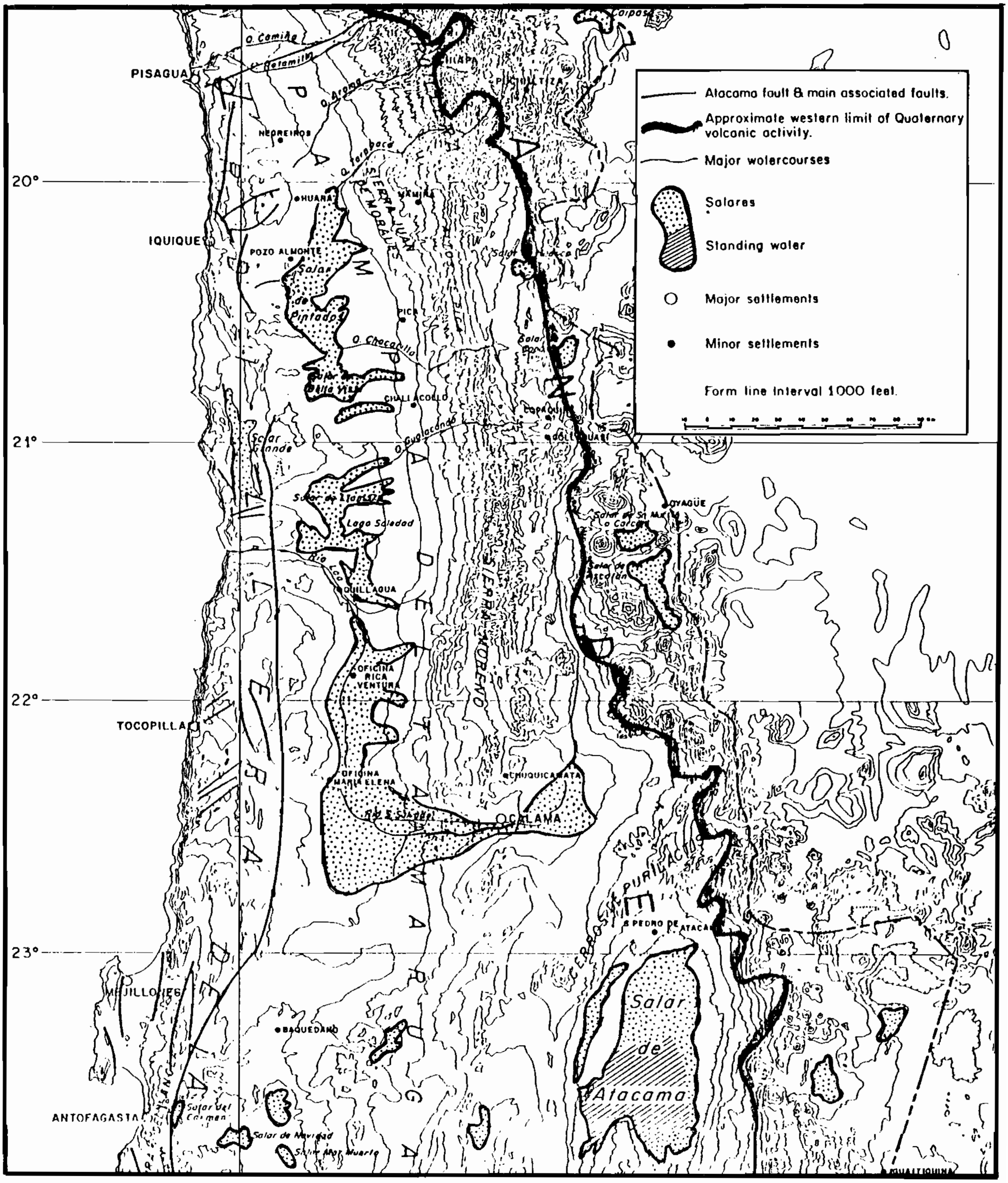

Fig. 3.4.1.- Maximum extension of the salars in northern Chile (Pampa del Tamarugal) (From Mortimer, 1980).

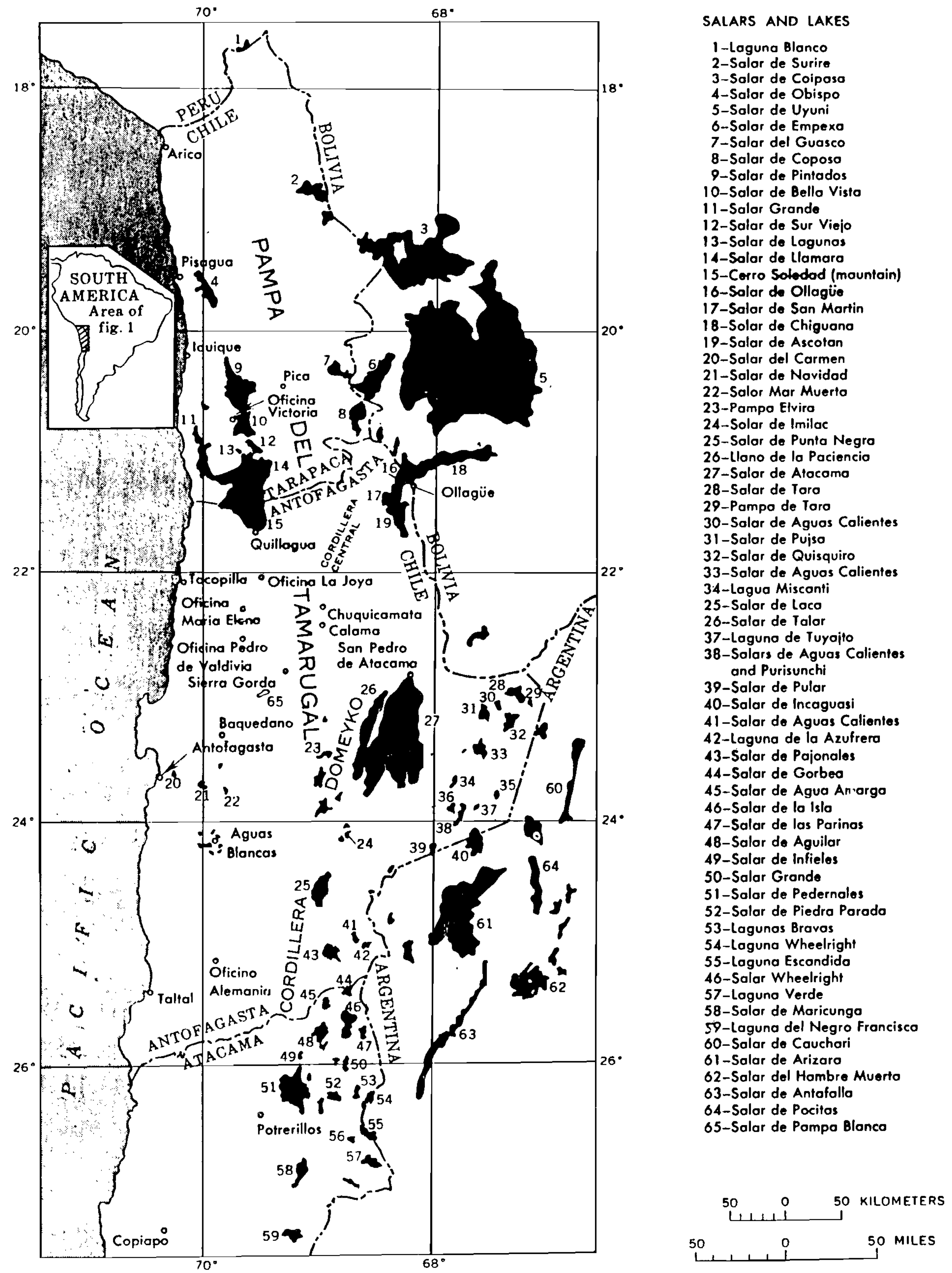

Fig. 3.4.2.- Location and list of the principal salars and lakes in northern Chile and surrounding areas (From Stoertz & Ericksen, 1974).

ABBREVIATED HISTORY OF *SALITRE*

Nelson Gallardo Ceballos
Departamento de Ingeniería
UNIVERSIDAD ARTURO PRAT

More than 100 *Oficinas Salitreras* (Nitrate Factories) filled the nitrate fields of the First Region of Tarapaca. This mining industry originated here more than 150 years ago (1830) with the resulting economic activity : The White Gold Era.

The mineral that was exploited and processed was the *caliche*. This can be defined as a complex of several kinds of rocks mixed with saline cement. The inert material is usually formed by volcanic rocks in different degrees of fractionation, in which sometimes interstratified calcareous rocks, some kind of clay and sandstones appear. Depending on the size of the rocks, the *caliche* appears as *pudinga* (pudding stone), conglomerate, breccla or sandstone, sometimes being so hard that in order to extract it, it is necessary to use explosives, and at some other times having an earthy consistency that allows an easy extraction. The saline cement contains the substance that is actually useful and the following compounds are found inside: sodium and potassium nitrates, salt, sulphates, borates and iodates, together with various other salts.

Processing the Raw Material : *Caliche*.

a) The System of *Paradas* (stops).

Name that derives from the word *parada*; in other words a rudimentary factory that kept moving towards the wealthier nitrate fields. It was used since approximately 1810 until the late part of the XIXth century. *Caliches* were selected by hand and processed with over 50 % of nitrate content and ground up to 5-8 cm. Afterwards, they were boiled with *agua vieja* (old water) for several hours with permanent stirring into steel containers heated with firewood which were called *cachuchos*. *Caliche* was added until the *caldo* (solution) acquired the appropriate density. The solution obtained in this manner was left to rest in order for the fine solids in suspension to settle, and it was sent afterwards to *bateas* (flat steel vats) where the nitrate crystallized through natural cooling. The remaining solution, the *agua vieja*, was used again for the treatment of a new load of *caliche*.

b) The Shanks System.

It was used until the mid-part of the XXth century. It was first introduced by Santiago Humberstone, in 1878. Mr. Humberstone is considered as the true founder of the Nitrate Industry. This system also used *caliches* selected by hand, with a minimum of 15 % in nitrates. The implementation of this system put an end to the anarchy that had existed so far in matters of devices and procedures. The factories were now more sophisticated

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from the engineering point of view, even though the basis of the system was still the process of dissolution in hot liquids (125°C) using *aguas viejas* (old waters). The solution of the first *cachucho* was successively poured into those in which the *caliches* were less lixiviated until the solution reached the saturation state : Methodical Lixiviation. The final and concentrated solutions were cleared and sent to *bateas* for their crystallization. Due to the fact that the *aguas viejas* also got enriched in iodine content, the iodine was normally recovered before the corresponding recycling.

c) The Guggenheim System.

It has been used since 1927. With this system *caliches* are processed within 6-8 % in nitrates, as a minimum. The grinding is intensified and the slimes generated are treated separately. The low grades of *caliches* are now compensated by the enormous size of the equipments. Thus, huge *bateas* (concrete vats) of more than 10,000 MT of capacity are lixiviated with *agua vieja*, although not boiling (only at 40°C), which circulates countercurrently. The concentrated solutions (*caldos*) cool down artificially through refrigeration to induce crystallization. The cold mother solution goes back to the vats refrigerating when passing the solution that goes out. The only factory (*Oficina Salitrera*) that used the Guggenheim System in the First Region Tarapaca was *VICTORIA*, which was definitely closed in 1979.

Around the year 1912, the Chilean Natural Nitrate supplied approximately 60 % of the world demand for Nitrogen. The First World War intensified the research in order to obtain Synthetic Nitrogen. So, the Guggenheim System that replaced the Shanks System arrived too late to keep an adequate competition. In 1938, the participation of Natural Nitrate in the world demand had gone down to 10 %. In 1958 a new crisis caused the abrupt collapse of this industry.

Around 1920 there were about 200 Shanks-type nitrate factories (*Oficinas Salitreras SHANKS*) in the whole nitrate zone of Northern Chile: Tarapaca y Antofagasta. Currently, there is only SOCIEDAD QUIMICA Y MINERIA DE CHILE S.A. (SOQUIMICH) with *MARIA ELENA* and *PEDRO DE VALDIVIA*.

The dumps of *caliche tailings* (tortas de ripio salitrero) and the numerous ghost towns nearby remain today, as silent testimonies of the intense economic and mining industrial activity of the past...

(Presentation to : 2nd Annual Meeting of IGCP 367 Project, Antofagasta - CHILE, November 19 - 26, 1995.)

THE PALEO-LAKE SOLEDAD

The existence and dimensions of a very large lake which would have existed at the end of the Pliocene have been matter of discussion for the last 50 years. According to Brüggen (1950), two conspicuous platforms preserved on the flanks of the cerro Soledad (21°S) (Fig. 3.0.4) represented lacustrine shorelines of a deep lake that he called Gran Lago Soledad. A that time, Pampa Tamarrugal was completely endorreic. Brüggen also hypothesized that an overflow of the lake and its drainage provoked the opening of the rio Loa canyon across the Cordillera de la Costa. Other authors (Mortimer & Saric, 1972, 1975; Rieu, 1975; Mortimer, 1980; Naranjo & Paskoff, 1982, 1985) discussed the relative effects of climate changes and tectonics on the evolution of the drainage regime and the formation of the rio Loa canyon. It is is commonly accepted that the opening of the lower course of rio Loa occurred at the beginning of the Pleistocene, but more precise data are required to strengthen the paleoclimatic and tectonic evolution of the area.

Fig. 3.0.4.- Lacustrine shorelines on the flank of the Cerro Soledad, which led Brüggen (1950) to infer the existence of a 200 m deep lake, called « Gran Lago Soledad », at the end of the Pliocene. The drainage of the lake would have played a major role in the genesis of the rio Loa canyon, across the Cordillera de la Costa (to the left of photograph). (Photo L.O.).

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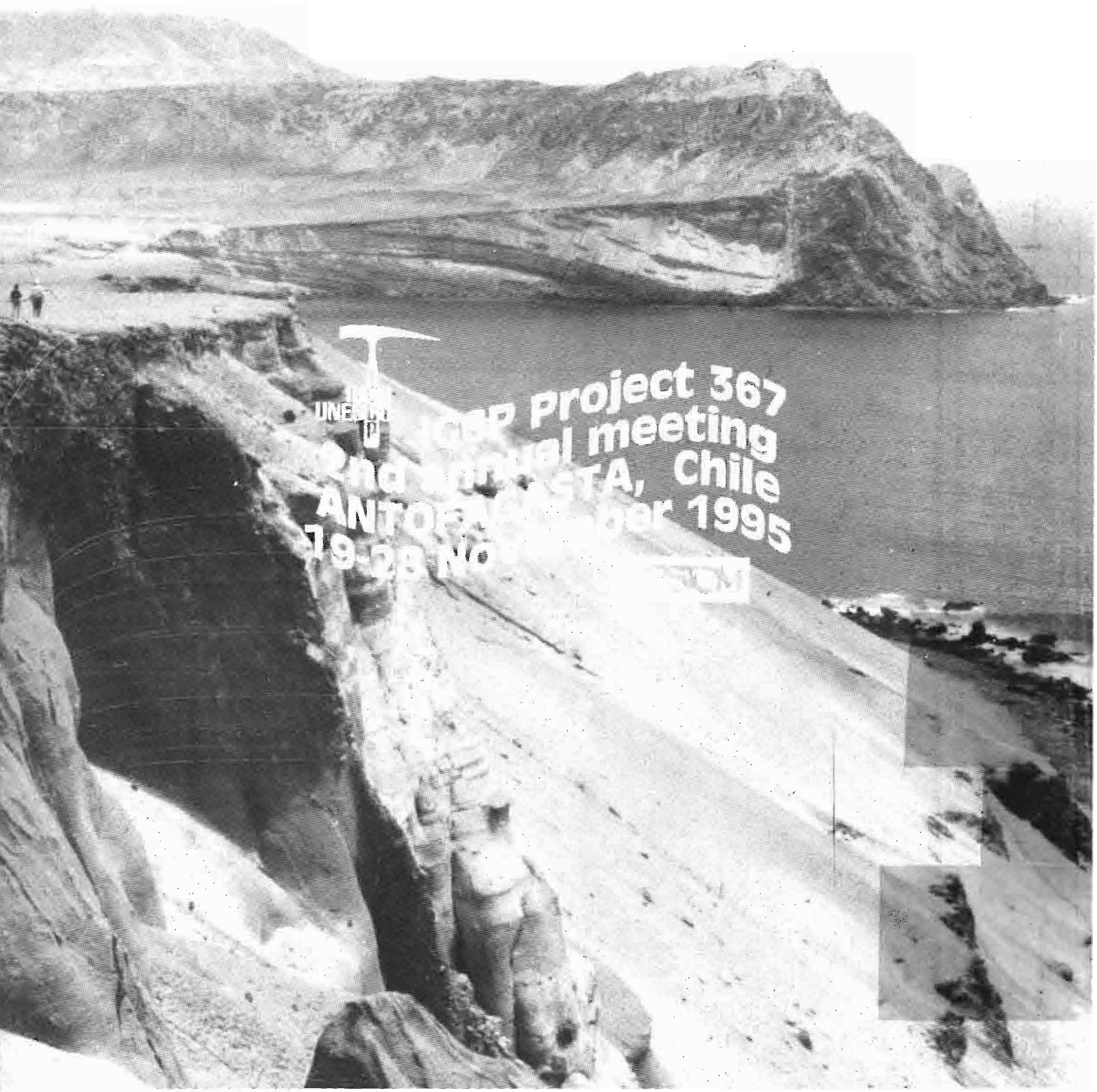
FOREWORD

The present fieldguide was prepared for the II annual meeting of IGCP Project 367, (Leader: D.S. Scott) to be held in Antofagasta, 19-28 November 1995. The organisation of the meeting itself and some unexpected events, like the earthquake which stroke Antofagasta on July 30, 1995, somewhat interfered with the preparation of the guide. As initially scheduled, the guide should have included more original results on various on-going scientific programmes. The lack of time did not permit to several involved scientists to contribute material on their current research timely. Laurent Serrurier, David Lazo, Jean-Claude Ruegg and Nelson Gallardo did send their contribution, and are thanked for their collaboration.

As usual in these circumstances, the compiler of this fieldguide had a hard time in trying to keep up with the printer delays (which he did not succeed!). Though, we still hope that the booklet will be in the hands of the participants on the first morning of the excursion... If it is the case, it will be because several persons helped heartily the main author. Special thanks are due, first of all, to Nury Guzmán, and also to Nelda Leiva, Jérôme Patoux, Ricardo Líbano, Sheila Saa, Liliana Castillo and others.

Gérard Hérail also played an important role in co-ordinating the edition of the volume.

Luc Ortlieb
and
J.L. Goy, Cari Zazo,
Cl. Hillaire-Marcel
& Gabriel Vargas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