

FIELD MEETING IN THE LA SERENA - COQUIMBO BAY AREA (CHILE)

**Guidebook for a fieldtrip
(27-28 November 1995)
organized during the 1995 Annual meeting of the
International Geological Correlation Program Project 367
(Antofagasta, Chile)**



Project 367

Roland PASKOFF

with the collaboration of
**E.M. LEONARD, J.E. NOVOA J., L. ORTLIEB,
U. RADTKE & J.F. WEHMILLER**

ORSIOM

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

Luc Ortlieb

ORSTOM (Institut Français de Recherche Scientifique pour le Développement en Coopération)
Universidad de Antofagasta & Universidad de Chile

David B. Scott

IGCP Project 367 Leader, Center for Marine Geology, Dalhousie University, Halifax (Canada)

Hernán Baeza

Facultad de Recursos del Mar, Universidad de Antofagasta

Sergio Barrientos

Departamento de Geofísica, Universidad de Chile (Santiago)

Guillermo Chong

Dirección General de Investigación y de Cooperación Científica, Universidad Católica del Norte

David Lazo

Departamento de Física y Matemáticas, Universidad Arturo Prat (Iquique)

Gérard Hérial

Representante de ORSTOM en Chile, & Depto. de Geología, Universidad de Chile (Santiago)

Principal Collaborators:

Renzo Follegati, Instituto de Estudios Oceanológicos, Univ. de Antofagasta

José Enrique Novoa, Depto. de Humanidades, Univ. La Serena, La Serena

Oscar Zúñiga, Dirección General de Investigación, Univ. de Antofagasta

Nury Guzmán, Fac. Recursos del Mar, Univ. de Antofagasta

Nelda Leiva, ORSTOM-Chile, Santiago

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.

FIELD MEETING IN THE LA SERENA - COQUIMBO BAY AREA (CHILE)

**Guidebook for a fieldtrip
(27-28 November 1995)
organized during the 1995 Annual meeting of the
International Geological Correlation Program Project 367
(Antofagasta, Chile)**



Project 367

Roland PASKOFF

with the collaboration of
E.M. LEONARD, J.E. NOVOA J., L. ORTLIEB,
U. RADTKE & J.F. WEHMILLER



1995

GENERAL CONSIDERATIONS

The marine terrace sequence in the Coquimbo Bay area of north-central Chile (29°50' S) is among the best known on the Pacific coast of South America (fig. 1). As a matter of fact, the surroundings of Coquimbo Bay represent a unique and impressive site because of the clearness of emerged, well-developed wave-cut platforms covered by fossiliferous beach deposits and separated by abandoned cliffs (photo. 1). The semi-arid climate of Mediterranean type (average annual rainfall: 127 mm, concentrated in winter time, with considerable variation from year to year) explains the good preservation of such a striking set of step-like marine terraces. Coquimbo Bay forms a 15-km long, north-south oriented embayment. The smaller (2 km long) Herradura Bay, immediately to the south, is here considered to be part of the Coquimbo Bay area. Climate is buffered by strong maritime influences. Mean seasonal air temperature variations is 7°C in amplitude (july: 11°6 C; january: 18°6 C). Coastal fogs, here called *camanchaca*, related to upwelling phenomena associated with the Humboldt cold current, are quite common (about 180 days of cloud cover in the surroundings of La Serena).

Historical account of geologic and geomorphic studies in the Coquimbo Bay area

Darwin (1846) was the first to draw attention to the scientific interest of the Coquimbo Bay whose marine terraces were actually first noticed by Captain B. Hall (1824) and already believed by C. Lyell (1833) to have been formed by the sea during the gradual rising of the land. The following are excerpts from Darwin's report " *Valley of Coquimbo*. (i.e. Río Elqui) - *The narrow coast-plain sends.... an arm, or more correctly a fringe on both sides, but chiefly on the southern side, several miles up the valley. These fringes are worn into steps or terraces which present a most remarkable appearance.... The first section, which I will give, is not drawn across the valley, but in an east and west line at its mouth, where the step-formed terraces debouch and present their very gently inclined surfaces towards the Pacific* (fig. 2). *The bottom plain (A) is*

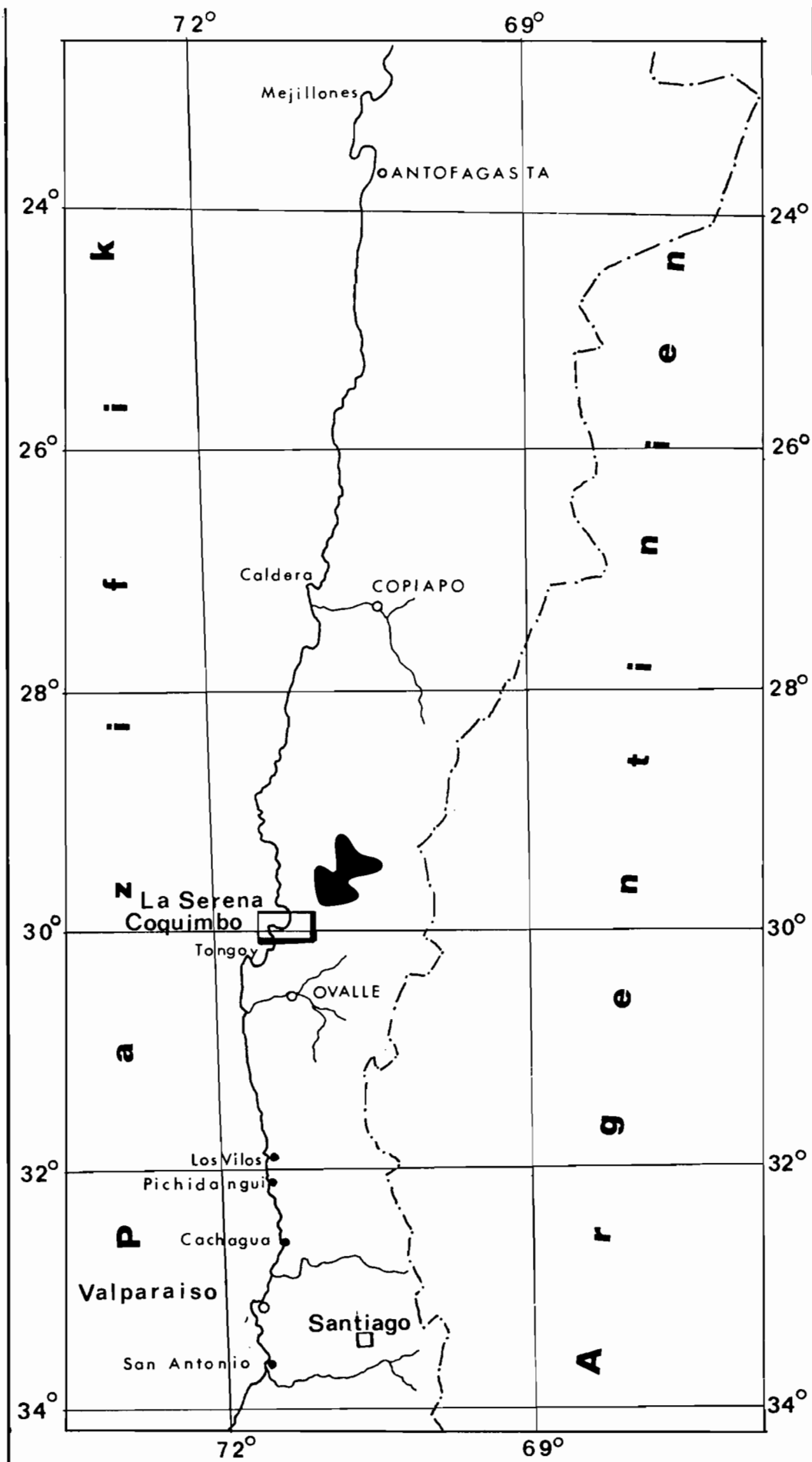


FIGURE 1. Location of the Coquimbo Bay area in north-central Chile.

2978

IGCP Project 367
2nd annual meeting
ANTOFAGASTA, Chile
19-23 November 1995

ORION



East and West Section through the Terraces at Coquimbo, where they debouch from the Valley, and front the Sea.

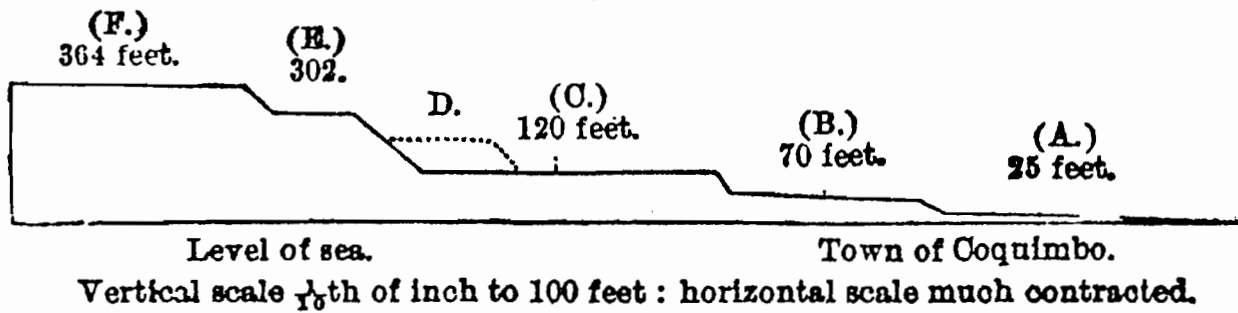


FIGURE 2. Cross-section showing the marine terraces south of La Serena, according to Darwin (1846).

about a mile in width, and rises quite insensibly from the beach to a height of twenty-feet at the foot of the next plain: it is sandy, and abundantly strewed with shells. Plain or terrace (B) is of small extent, and is almost concealed by the houses of the town (i.e. La Serena), as is likewise the escarpment of the terrace (C). On both sides of a ravine, two miles south of the town, there are two little terraces, one above the other, evidently corresponding with (B) and (C); and on them marine remains are plentiful. Terrace (E) is very narrow, but quite distinct and level; a little southward of the town there were traces of a terrace (D) intermediate between (E) and (C). Terrace (F) is part of the fringe-like plain, which stretches for the eleven miles along the coast; it is here composed of shingle, and is 100 feet higher than when composed of calcareous matter. This greater height is obviously due to the quantity of shingle, which at some former period has been brought down the great valley of Coquimbo. Considering the many shells strewed over the terraces (A) (B) and (C), and a few miles southward on the calcareous plain, which is continuously united with the upper step-like plain (F), there cannot, I apprehend, be any doubt, that these six terraces have been formed by the action of the sea; and that their five escarpments mark so many periods of comparative rest in the elevatory movement, during which the sea wore into the land. The elevation between these periods may have been sudden and on an average not more than seventy-two feet each time, or it may have been gradual and insensibly slow. From the shells on the three lower terraces, and on the upper one, being all littoral and sublittoral species,and lastly from a slow rising lately or still in progress here, it appears to me far probable, that the movement has been slow. The existence of these successive escarpments, or old cliff-lines, is in another respect highly instructive, for they show periods of comparative rest in the elevation movement, and of denudation". To sum up, in the Coquimbo Bay area, Darwin identified five main elevated marine terraces which he believed to have been formed by sea erosion during periods of rest in a gradual elevation of the land. He also noticed that shells of still existing species, but not in the same proportion as on the present beaches, are embedded in deposits, locally called *losa* (hard deposits of beach sands and gravels with abundant shells cemented by calcareous material), which lie on the surface of the terraces. These surficial deposits rest on a thick Tertiary formation containing shells, apparently largely extinct.

I. Domeyko (1848), who apparently ignored Darwin's publication, reports four topographic levels of marine origin around Coquimbo bay. Hereafter are quotations from his paper. "*La ville de Coquimbo (i.e. La Serena), situéeà 1 km de la mer, se trouve au centre d'une ancienne baie qui avait à peu près la même forme que la baie actuelle (fig. 3). La surface du terrain abandonné par cette ancienne baie s'élève par étages, sous forme d'un amphithéâtre présentant des lignes d'érosion.... concentriques au rivage actuel. Il y en a quatre bien visibles qui aboutissent aux extrémités du grand arc de la baie moderne, et qui ne sont interrompues que*

Fig. 1 Carte géologique des environs de Coquimbo.

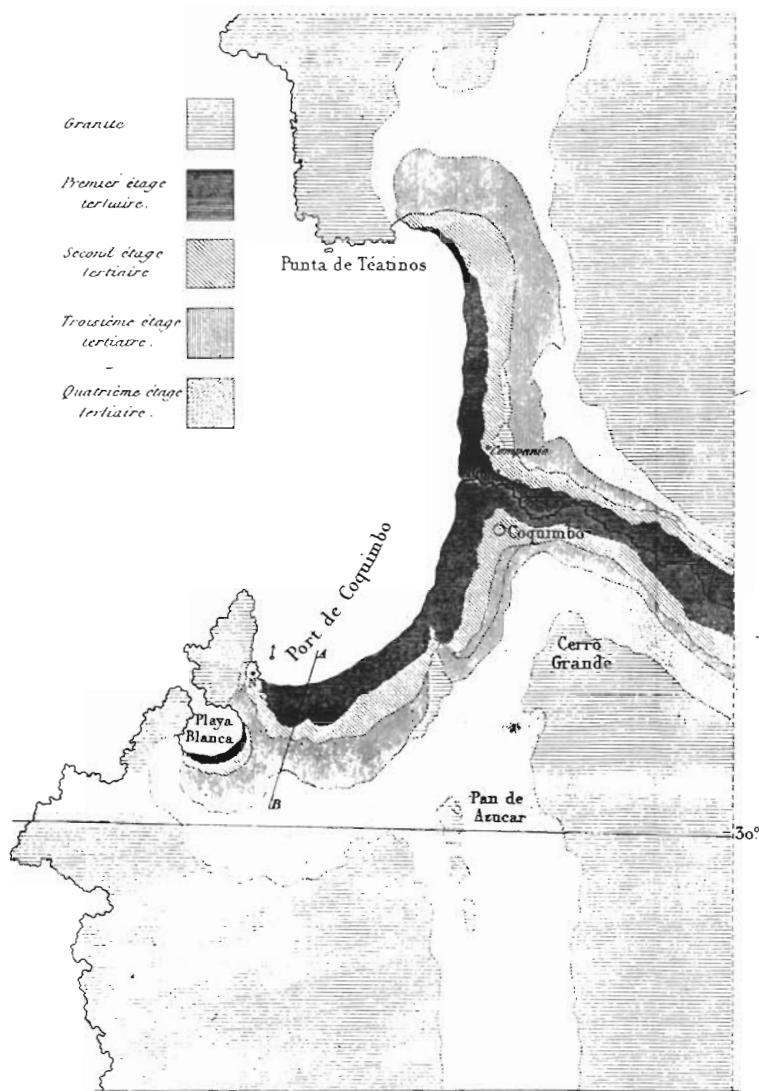


Fig. 2 Nivellement et Vue de la surface des quatre étages modernes, suivant la ligne A B. (Fig. 1)

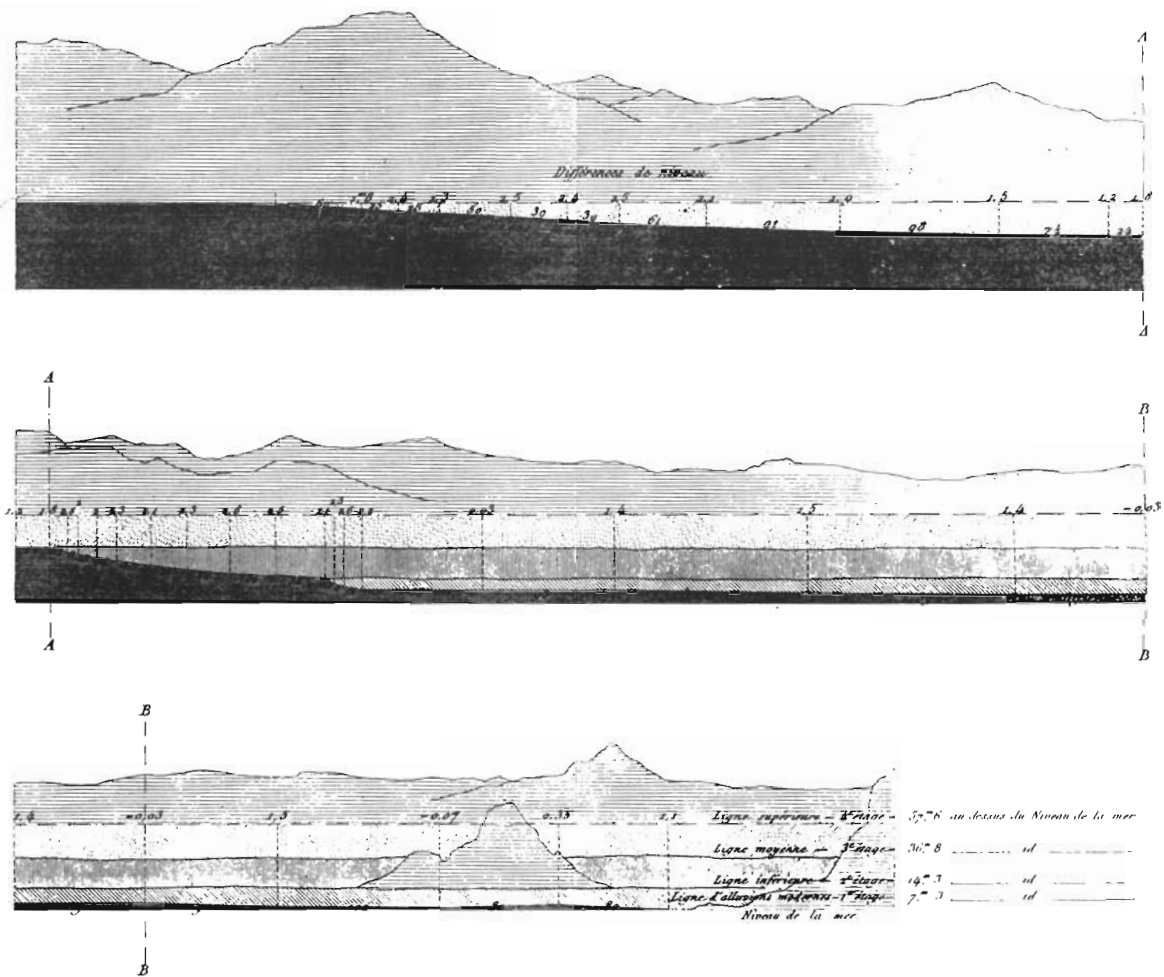


FIGURE 3. The marine terraces of the Coquimbo Bay area, according to Domeyko (1848).

par la grande vallée de Coquimbo (i.e. Río Elqui) qui coupe tout le terrain tertiaire, et sur les flancs gazonnés et fortement inclinés de laquelle, les étages ci-dessus forment autant de terrasses presque horizontales.... Tout le terrain tertiaire des environs de Coquimbo est de formation très moderne et récemment sorti du sein de l'Océan.... La disposition en gradins de la surface de ce terrain est une preuve de l'irrégularité du mouvement ascensionnel de la côte. Reste à savoir si les quatre lignes d'ancien niveau bien caractérisées qu'elle présente, correspondent à quatre époques d'une ascension plus rapide que l'ascension continue à laquelle on supposerait soumise cette côte, ou bien à quatre époques d'un repos prolongé.... Pour expliquer la formation des pentes très douces des quatre étages du terrain tertiaire de Coquimbo et des trois talus intermédiaires qui relient ces étages, [on est amené] à admettre que dans le mouvement ascensionnel de la côte il y a eu quatre longues périodes d'un mouvement extrêmement lent et trois courtes périodes d'un soulèvement beaucoup plus rapide.... Nous sommes conduits à penser qu'en général les phénomènes de cette nature, loin de dépendre de circonstances locales, tiennent à des causes qui influent sur les grandes révolutions du globe terrestre et qui agissent sur les deux hémisphères à la fois". Therefore, Domeyko's conclusion on the genesis of the marine terraces found around the Coquimbo Bay area agrees with that of Darwin.

J. Brügger (1929), a geologist who in the first half of this century was the pioneer of the geomorphic research in Chile, showed that it exists an unconformity between the surficial deposits associated with the wave-cut terraces and the underlying marine strata. He wrote: "*La estructura de [las terrazas] es muy sencilla: encima de las capas del Plioceno algo inclinadas yacen las capas horizontales del Cuaternario, que nos indican una interrupción de la sedimentación entre ambas formaciones. La discordancia entre el Cuaternario y el Plioceno indica que temporalmente el mar debe haberse retirado de la región, debido a un solevantamiento del continente, volviendo después a causa de un nuevo hundimiento.... La terraza principal desciende en cuatro escalones hasta el nivel del mar.... Los escalones indican una serie de solevantamientos interrumpidos por épocas estables, en que las olas excavaron pequeñas plataformas de abrasión en el declive de la terraza principal*". So, according to Brügger, the wave-cut platforms around Coquimbo Bay are the products of an alternation of rising and sinking movements, the general result being an uplift of the land.

The Coquimbo Formation

The terraces in the Coquimbo Bay area are cut onto Tertiary sediments of the the so-called Coquimbo Formation, according to Darwin's informal proposal, mainly represented by fossiliferous ill-cemented sandstones, about 250 m thick, which gives evidence of a transgression.

The ocean invaded lowlands limited by tectonic blocks of volcanic and intrusive rocks of Cretaceous age, controlled by north-south oriented faults, which formed peninsulas or islands at the culmination of the transgression (fig. 4). Afterwards, the coastal horsts protected the sediments left by the transgression from a complete removal by sea erosion. The ocean also entered into the mouth of the Elqui River whose lower course had been deepened during a previous phase of strong erosion in relation with a sea level much lower than the present one. At the time of the culmination of the transgression, sea-level reached an elevation of about 200 m above the present one.

The Coquimbo Formation is exclusively composed of neritic or sublittoral sediments. The distinctive lithofacies corresponds to poorly cemented, medium to fine grained sandstones, generally yellowish, but sometimes also greenish, whitish or greyish, with some gravel beds and conglomerates. The carbonate content is low (less than 5%). Quartzose grains are well sorted. The Coquimbo formation shows an internal erosional unconformity (fig. 5; photo 2), pointing to a fall in sea-level which has been recognized over the entire coast of north-central Chile. The lower sedimentary unit has several distinctive facies which may be interpreted in terms of physical and depositional environments. Typical for the lower unit are conglomerates rich in shell debris and fossiliferous cross-bedded, coarse-grained sandstones. The upper unit shows a coarse sedimentation only on the shores of the former bay and, evidently, at the mouth of the Elqui River where rounded pebbles including sandy lenses are found. Elsewhere, medium-to fine-grained, rich in shells sandstones represent the most common facies, beside fossiliferous siltstones, coquinas, and conglomeratic lenses which are interpreted as deposits of nearshore currents. On the whole, the strata of the Coquimbo Formation do not show major tectonic deformation Since their deposition, the effects of crustal movements have been here remarkably discreet.

Fossils collected from the surroundings of Coquimbo were first described by A. d'Orbigny (1842) who ascribed the Coquimbo Formation to the Miocene. From a detailed study of its fauna, W. Möricke and G. Steinmann (1896) induced a Neogene age for the formation. Much later, D. Herm (1969) was involved in a thorough research, paying special attention to the evolution of the Upper Tertiary marine fauna along the coast of Chile between 22° S and 34° S latitude, and he concluded that the Coquimbo formation was Pliocene in age. However, according to a more recent investigation carried out by R. Martinez (1979) in the adjoining area of Tongoy (30°15' S), based on microfossils (foraminifera pertaining to the species *Virgulinitella pertusa* and *Florilus grateloupi*), the Coquimbo Formation should actually be ascribed to the middle to upper Miocene. This new chronologic view is appealing since it fits better the bio- and

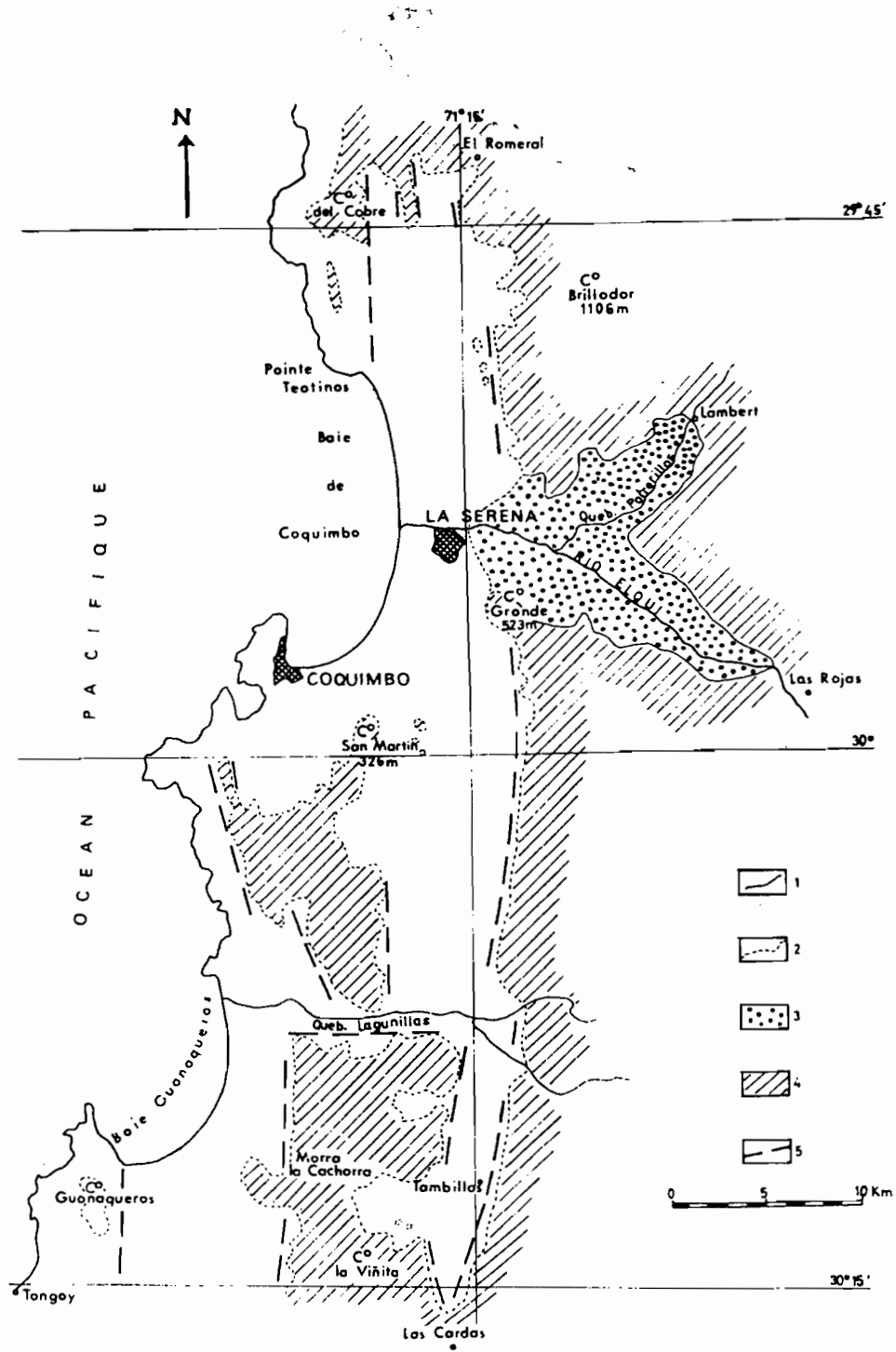


FIGURE 4. Extension of the middle to upper Miocene transgression in the Coquimbo Bay area (Paskoff, 1970).

- 1: present shoreline. 2: shoreline at the time of the culmination of the Miocene transgression. 3: Miocene deltaic deposits of the Elqui River. 4: emerged landforms in Miocene times. 5: Pre-Miocene faults

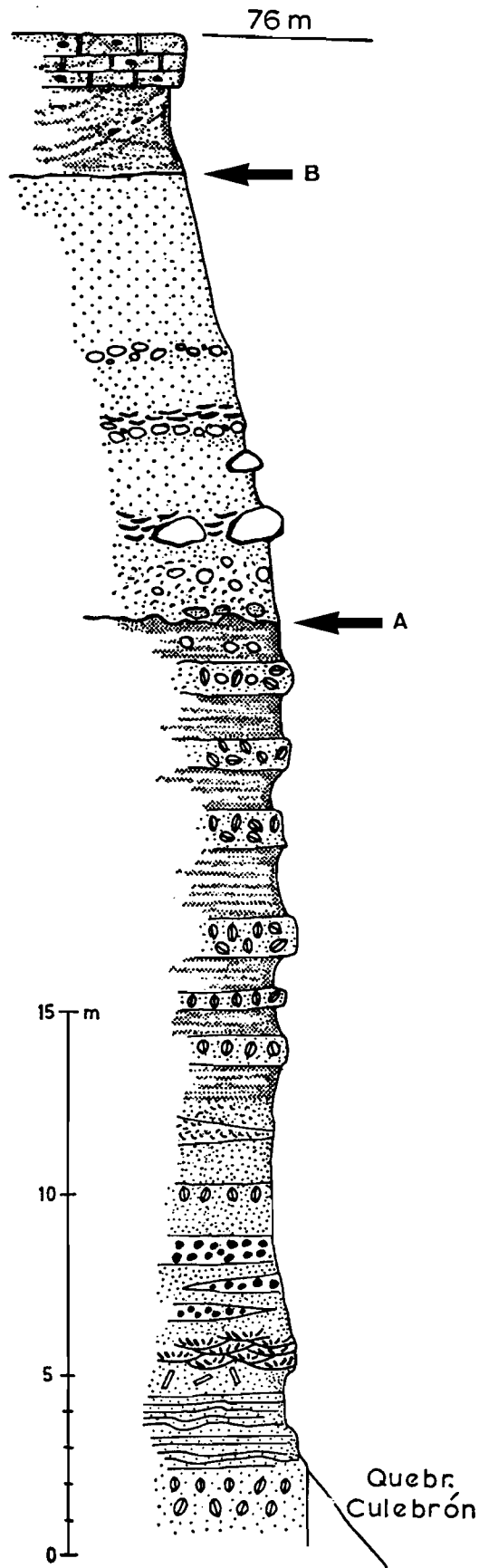


FIGURE 5. Bluff of the Quebrada Culebrón, Rincón San Martín, east of Coquimbo, showing two unconformities, one (A) within the Coquimbo Formation (middle to upper Miocene), the other (B) between sandstones of the Coquimbo Formation and overlying beach deposits capping the Serena II terrace (Herm, 1969).



PHOTO 2. Soft yellowish sandstones of the Coquimbo Formation (middle to upper Miocene) visible on a bluff, Quebrada Culebrón, Rincón San Martín, east of Coquimbo (photo. R. Paskoff).
Erosional unconformities A and B are explained in figure 5.

chronostratigraphic correlation chart of marine Neogene sequences, now used on the Pacific coast of South America (Tsuchi, 1992), and showing a middle Miocene cooling. Such a first moderate cooling was noticed by D. Herm in the molluscan assemblages of the Coquimbo Formation which is largely deprived of "Atlantic" genera and species adapted to warm waters. The revised age of the Coquimbo formation also is in agreement with the radiochronologic framework of the geomorphic evolution of the southern part of the Atacama desert (Naranjo and Paskoff, 1980). North of La Serena, in the Río Salado area (26°20' S), K/Ar datings of volcanic materials interbedded with continental Cenozoic deposits which laterally grade into marine strata, considered as an equivalent of the Coquimbo Formation, yielded middle to upper Miocene ages. Among the fauna of the Coquimbo formation, D. Herm (1969) found that about 55% of its species and sub-species have since disappeared from the South Pacific American coast, the majority of these now being extinct; 15% are still living, but in warmer waters at lower latitudes; finally, of the 30% that can still be found on the present beaches, there are differences in size and relative frequency. According to the same author, the following fauna would be characteristic of the Coquimbo Formation: *Oculina remondi* PHIL.; *Turritella cingulatiformis* MÖR.; *Fusus remondi* PHIL.; *Monoceros blainvillei* D'ORB.; *M. pyrulatus* PHIL.; *M. tenuis* PHIL.; *M. mirabilis* MÖR.; *Chlamis simpsoni* (PHIL.); *Chl. vidali* (PHIL.); *Pinna* sp.; *Magellania macrostoma* (PHIL.). A conspicuous regression, known as the Tongoyan regression (Paskoff, 1968) and evidenced by discontinuous continental deposits including fresh water molluscs, followed the deposition of the Coquimbo formation

The genesis of the wave-cut platforms

In the sixties, the Coquimbo Bay terraces were carefully reexamined by D. Herm and R. Paskoff who carried out a detailed geomorphic, stratigraphic, and paleontological work (Herm and Paskoff, 1967; Herm, 1969; Paskoff, 1970). In the southern part of the bay for which a 1:50 000 scale colored geomorphic map is available (a copy of it is included in the guidebook), five main terraces, rising from the present sea-level to an elevation of about 120-130 m at the foot of the surrounding highlands, were identified (fig. 6). Here, all are cut onto the soft sandstones of the Coquimbo formation (fig. 7). Contrary to the opinion expressed by earlier researchers, who insisted on the tectonic instability of the coast and interpreted the terraces as a result of a single withdrawal of the sea due to an uplift of the continent interrupted by episodes of rest or sinking, D. Herm and R. Paskoff thought that the Coquimbo area was a relatively stable area and attributed the formation of the terraces to sea level fluctuations of glacio-eustatic origin. At the

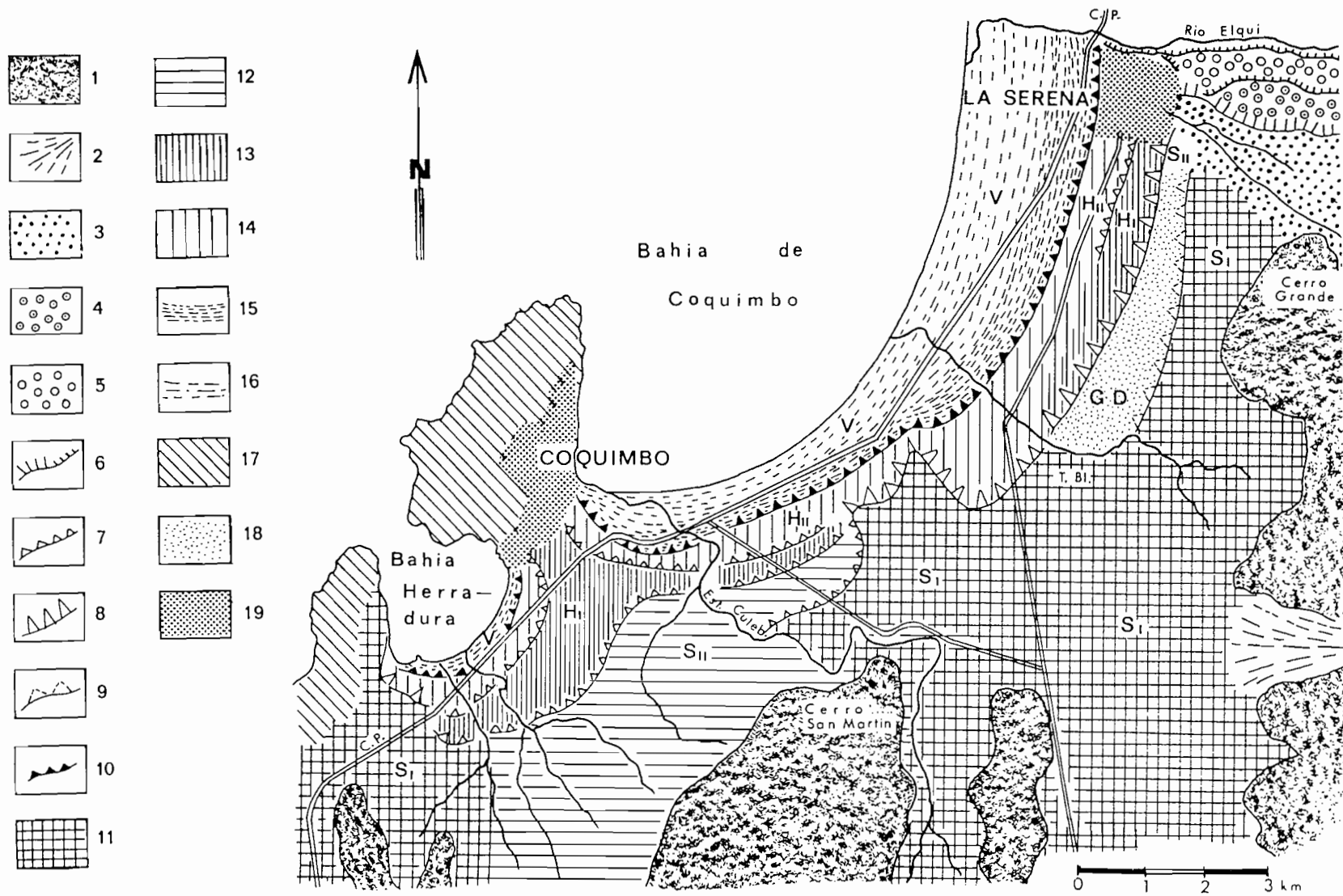


FIGURE 6. Geomorphic sketch of the southern part of the Coquimbo Bay area (Herm and Paskoff, 1967).

1: hill (lower Cretaceous volcanic and sedimentary rocks). 2: alluvial fan. 3: higher terrace of the Elqui River. 4: middle terrace of the Elqui River. 5: lower terrace of the Elqui River. 6: edge of fluvial terrace. 7: abandoned cliff (less than 20 m high). 8: abandoned cliff (more than 20 m high). 9: buried abandoned cliff. 10: Holocene abandoned cliff. 11: Serena I (S1) marine terrace. 12: Serena II (SII) marine terrace. 13: Herra-dura I (HI) marine terrace. 14: Herra-dura II (HII) marine terrace. 15:

Holocene marinedeposits older than 2,000 yr B.P. 16: Holocene marine deposits younger than 2,000 yr B.P. 17: bedrock (Jurassic/lower Cretaceous intrusive rocks) eroded by marine abrasion in Cenozoic times. 18: old dune (GD). 19: buildings. V: Vega terrace. C.P: Pan American Highway.

W

E

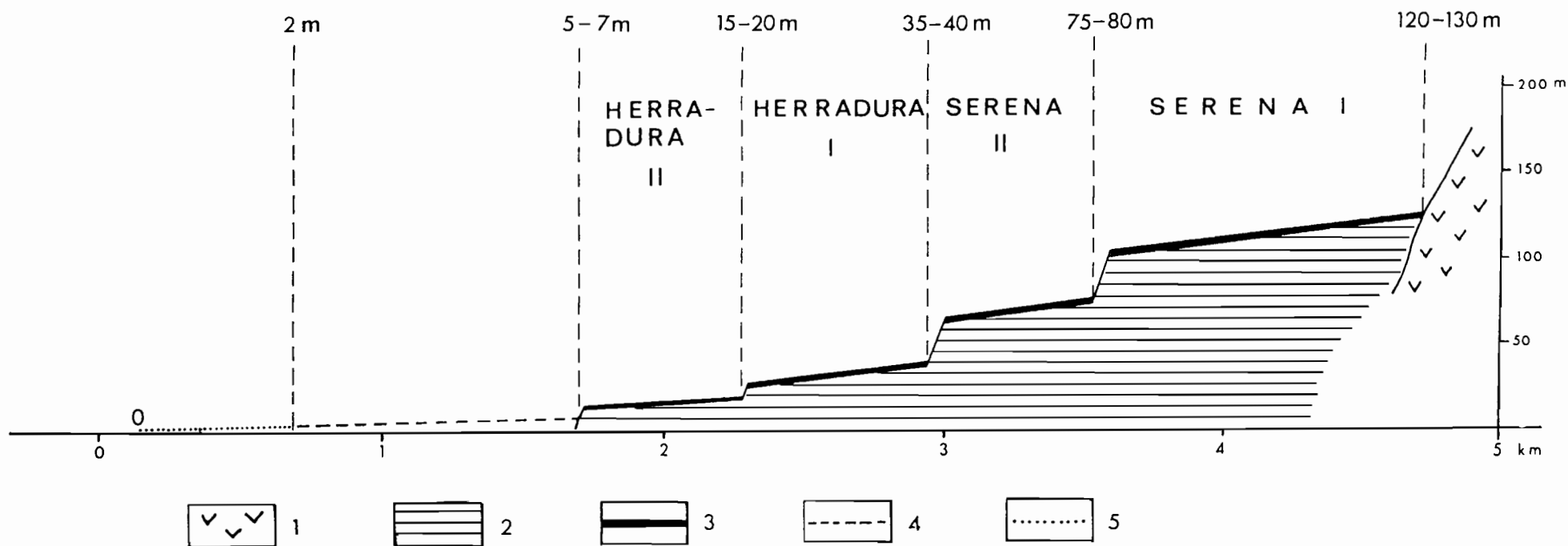


FIGURE 7. Cross-section showing the marine terraces in the southern part of the Coquimbo Bay area (Herm and Paskoff, 1967).

1: bedrock. 2: sandstones of the middle to upper Miocene Coquimbo Formation. 3: Surficial beach deposits of the Serena I, Serena II, Herradura I, Herradura II wave-cut terraces. 4: Holocene marine deposits older than 2,000 yr B.P. 5: Holocene marine deposits younger than 2,000 yr B.P.

time of their investigations, Zeuner's idea (1959) that a progressive sea-level drop of about 100 m had occurred in Quaternary times for tectono-eustatic reasons was still considered as valid. We now know that this view is largely illusory. Therefore, it is clear that the terraces are the result of Plio-Quaternary transgressions and regressions, linked with sea-level fluctuations of glacio-eustatic origin, which were superimposed on a slow general uplift of the continent. No evidence of faulting or warping affecting the terraces has been found so far in the southern part of the Coquimbo Bay. The terraces are capped by rather thin beach sediments in which sands, pebbles, and shells are mixed. Frequently, on the higher terraces, these sediments are consolidated by a calcareous cement, resulting in the locally called *losa* which may be used as a building stone. The surficial deposits lying on the terraces are always separated from the underlying strata of the Coquimbo Formation by a clear erosional unconformity. In some places, it is possible to distinguish transgressive deposits from regressive deposits. The former often include pebbles made from the underlying sandstones, resembling basal conglomerates, whereas the latter are mainly composed of stratified sands with few pebbles. It is now firmly established that glacio-eustatic sea-level fluctuations were the dominant factor in forming the terraces of the Coquimbo Bay area, and tectonic vertical movements simply separate the wave-cut platforms of successive interglacial intervals.

As far as the fauna associated with the deposits capping the wave-cut terraces of La Serena is concerned, it shows some differences with the one found in the strata of the Coquimbo Formation (Herm, 1969). A move toward isolation and endemic development is noticeable. This change is apparent through: (1) an increasing reduction of genera (*Anomia*, *Panope*, *Isognomon*, *Anadara*), mostly forms desiring warmth; (2) reduction of the number of species, especially among the genera *Chlamys* and *Chorus* (for instance, only one *Chlamys* is found in terrace deposits, *Chlamys purpurata*, in contrast to five in the Coquimbo Formation); (3) substitution of the dominant species in the faunal communities; and (4) extensive development of several species which appear in the Coquimbo Formation only as accessory forms (*Mesodesma donacium*, *Mulinia* div. sp.). During all the time of the terrace formation, the marine fauna remained relatively constant and appears to be quite similar to the present one.

The age of the wave-cut platforms

The flight of terraces surrounding Coquimbo Bay long remained poorly dated and we must recognize that still it is. In this respect, the first systematic attempt was made by D. Herm and R. Paskoff (1967). They suggested that the terraces date from the Pleistocene interglacial high sea-level stands: the lowest but one (Herradura II) from the last interglacial period, the next

higher (Herradura I) from the penultimate interglacial period. The two highest terraces (Serena II and Serena I) were considered to be of early Pleistocene age. These age assignments were largely conjectural, based on archaeological evidence and a Holocene- age minimum limiting radiocarbon date on the deposits covering the lowest platform (the Vega terrace) and the post-Coquimbo (at that time considered as Pliocene) nature of the fauna found in the beach deposits capping the terraces. The chronologic sequence defined at Coquimbo Bay was considered as a reference sequence for marine stages for northern Chile and therefore was correlated to other sites along the more than 1 000 km of coastline on the basis of relative position and altitude of terraces (Herm, 1969; Paskoff, 1970).

Marine stages	Highest elevation (m) at Coquimbo Bay	Proposed age
Vega	5-7	Holocene
Herradura II	15-20	Ultimate interglaciation
Herradura I	35-40	Penultimate interglaciation
Serena II	75-80	Early Pleistocene interglaciation
Serena I	120-130	Early Pleistocene interglaciation

Table 1. Marine stages in the Coquimbo Bay area as proposed by Herm and Paskoff (1967) , modified by Paskoff (1977)

It must be added that R. Paskoff (1970) assumed that the Vega terrace had been actually cut during the last glaciation by an interstadial transgression (the so-called Cachagua episode) which approached the present sea-level but remained below it (stage 3 ?) The terrace was entirely reoccupied and reworked at the time of the culmination of the Holocene transgression. Afterwards, an emergence took place.

Recent geochronological studies

Within the last decade, modern dating techniques have been used to try to refine the chronological framework of the marine terraces around Coquimbo Bay (Radtke, 1987a and b, 1989; Hsu *et al.*, 1989; Leonard and Wehmiller, 1992). Th/U dating of coral can provide reliable numerical ages for Quaternary terrace deposits but, so far, no coral has been found in the terrace deposits at Coquimbo Bay. As a result, the terrace sequence there remains undated by established numerical methods. Recent attempts to date the sequences have used more experimental techniques: electron spin resonance (Radtke, 1987a and b; Radtke, 1989) and amino acid

geochronology (Hsu *et al.*, 1989; Leonard and Wehmiller, 1992). Electron spin resonance (ESR) has provided the first numerical ages for terrace deposits (table 2). Last interglacial deposits have been identified and differentiated from older deposits using ESR, but assigning specific ages to the older units is problematic. At the temperatures found in coastal semi-arid Chile, ESR ages older than about 200,000 yr must be regarded as minimum ages, and the older units nearly always yield a significant scatter of ages. ESR data indicates that the Herradura II terrace is of last interglacial age although older shells were found on it at one site. Based on a large number of minimum limiting ESR ages, U. Radtke (1989) concluded that the Herradura I terrace predates the penultimate interglaciation and may include shells of two ages separated by an unconformity. He surmised that both the absence of a terrace of the penultimate interglaciation and the unconformity result from terrace reoccupation due to low uplift rates. That uplift rate in the Coquimbo bay area has been slow enough to allow terraces formed during one high sea-level stand to be reoccupied during one or more subsequent high stands has also been suggested by J.T. Hsu *et al.* (1989) on the basis of their initial analysis of amino acid data.

Further studies on aminostratigraphy of fossil molluscs collected on the terraces of the Coquimbo Bay area (Leonard and Wehmiller, 1992), brought new valuable data. The method is based on measurement of the extent of *post mortem* diagenesis of amino acids in shell protein, most commonly the epimerization of L-isoleucine to D-alloisoleucine (generally expressed as a ratio $A/I = \text{D-alloisoleucine/L-isoleucine}$). A/I values increase *post mortem* from zero to an equilibrium value ca. 1.3, as a function of time, temperature, and molluscan taxa. Relative ages can be derived from A/I values of suites of samples if similar temperature histories can reasonably be assumed. Derivation of numerical age estimates from A/I values requires an independent age calibration and an appropriate kinetic model for epimerization.

E.M. Leonard and J.F. Wehmiller used A/I values in *Protothaca* and *Mulinia* to establish relative and approximate numerical ages for the Herradura II and Herradura I terraces of the Coquimbo Bay area along three transects (fig. 8). The relative age chronology indicates that each terrace was occupied during more than one high sea-level stand, probably as a result of low net uplift rates. Approximate numerical ages for the deposits were determined using last interglacial electron spin resonance ages of U. Radtke (1989) as a local calibration, and a kinetic model for epimerization in *Protothaca* developed in California (Wehmiller *et al.*, 1988). Results of recent Th-U dating of coral from a terrace deposit near Caldera (27°04' S) induced E.M. Leonard *et al.* (1994) to propose a possible modification of the kinetic model for Chilean samples.

Sample(Lab.No.) (Th/U-Lab.No.)	U-238 (ppm)	Th-232 (ppm)	U-234 U-238	Th-230 U-234	Th-230/U-234-age (yr)	Accumulated Dose (AD)(Gy)	Annual Dose (D ₀)(mGy/yr)	ESR-age (±15%)	Genus, species
Herradura (II)									
D-692-a (Hd 923)	1.09 ±0.017	0.007 ±0.003	1.22 ±0.013	0.84 ±0.02	160,000 +10,000 -6,000	150.5	1.079	139,400	<i>Dosinia sp.</i>
D-692-b (Hd 1202)	0.61 ±0.016	0.215 ±0.01	1.28 ±0.05	0.782 ±0.024	132,000 +8,000 -7,000 (corr. 114,000 + 9,000 -8,000)	92.4	0.974	94,900	<i>Mulinia edulis</i> (KING)
D-718-a (Hd 1004)	1.80 ±0.05	0.1 ±0.01	1.17 ±0.04	0.81 ±0.04	154,000 +24,000 -10,000	210.9	1.785	118,000	<i>Mulinia edulis</i> (KING)
D-718-b (Hd 1204)	1.96 ±0.002	0.055 ±0.007	1.20 ±0.02	0.692 ±0.011	112,400 +4,000 -4,000	182.8	1.752	112,000	<i>Mulinia sp.</i>
D-936-a (Hd 1200)	2.13 ±0.02	0.017 ±0.03	1.60 ±0.02	0.95 ±0.014	180,000 +10,000 -5,000	330.9	1.597	≥208,000	<i>Mulinia edulis</i> (KING)
Herradura (I)									
D-696-a (Hd 934)	1.80 ±0.06	0.014 ±0.007	1.27 ±0.05	1.27 ±0.24	>280,000	382.9	1.064	≥361,000	<i>Protothaca</i> (MOLINA)
D-696-b (Hd 987)	1.88 ±0.03	0.03 ±0.006	1.23 ±0.03	1.00 ±0.02	>350,000	288.7	0.873	≥332,000	<i>Protothaca sp.</i>
D-926 (Ku 377)	1.583 ±0.03	0.050 ±0.028	1.288 ±0.018	0.968 ±0.034	262,000 +45,200 -32,300	314.9	0.959	≥329,000	n.d.
D-1149-a	0.839 ±0.029	0.061 ±0.015	1.109 ±0.049	1.012 ±0.056	>350,000	205.4	1.074	≥191,000	<i>Turritella cingulata</i> (SOWERBY)
D-1149-b	1.069 ±0.01	-	1.141 ±0.048	-	Th-excess	216.2	0.981	≥221,000	<i>Turritella cingulata</i> (SOWERBY)
D-1150-b (Hd 1630)	1.44 ±0.03	0.04 ±0.008	1.48 ±0.05	0.866 ±0.02	150,000 +10,000 -9,000	199.1	1.291	154,000	<i>Eurhoma- lea rufa</i> (LAM.)
Quebrada El Romeral/ Quebrada Angostura									
D-708-a (Hd 925)	1.10 ±0.03	0.037 ±0.01	1.59 ±0.06	0.976 ±0.03	200,000 +20,000 -15,000	303.5	2.431	124,800	<i>Protothaca thaca</i> (MOLINA)
D-708-b (Hd 990)	2.03 ±0.03	0.02 ±0.001	1.20 ±0.02	1.28 ±0.06	Th-excess	252.7	2.576	99,300	<i>Protothaca thaca</i> (MOLINA)
D-1153-a (Hd 1624)	4.77 ±0.15	0.06 ±0.01	1.41 ±0.01	0.79 ±0.03	128,000 +8,000 -8,000	224.7	2.341	96,100	<i>Protothaca thaca</i> (MOLINA)

D-691-a (Hd 913)	1.22 ±0.03	0.014 ±0.006	1.71 ±0.05	1.29 ±0.037	>350,000	652.6	1.440	≥454,000	<i>Mesodes- ma donaci- um</i> (LAM.)
D-695-a (Hd 933)	1.56 ±0.03	0.082 ±0.013	1.31 ±0.04	1.09 ±0.02	>350,000	507.1	1.673	≥303,000	<i>Mesodes- ma donaci- um</i> (LAM.)
D-927 (Ku 376)	1.033 ±0.021	0.053 ±0.011	1.259 ±0.021	0.922 ±0.035	226,600 +32,300 -24,800	261.2	1.264	≥207,000	n.d.
D-935-a (Hd 1199)	0.313 ±0.01	0.007 ±0.002	1.42 ±0.07	0.988 ±0.04	225,000 +55,000 -35,000	287.7	1.305	≥221,000	<i>Mesodes- ma donaci- um</i> (LAM.)
D-1157-a	0.635 ±0.043	0.035 ±0.011	1.205 ±0.105	1.242 ±0.107	>350,000	400.0	1.291	≥310,000	<i>Eurhoma- lea sp. (?)</i>
D-1158-a (Hd 1632)	1.61 ±0.04	0.17 ±0.02	1.87 ±0.07	1.18 ±0.04	>320,000	644.1	1.682	≥383,000	<i>Mesodes- ma donaci- um</i> (LAM.)
D-1159-a (Hd 1642)	1.32 ±0.02	0.02 ±0.005	1.82 ±0.04	1.20 ±0.001	>350,000	571.0	1.289	≥443,000	<i>Pelecypoda indet.</i>

Table 2. Th/U and ESR ages of Herradura II and Herradura I terraces at Herradura Bay and at Quebrada El Romeral/Quebrada Angostura, Coquimbo Bay area (Radtke, 1989)

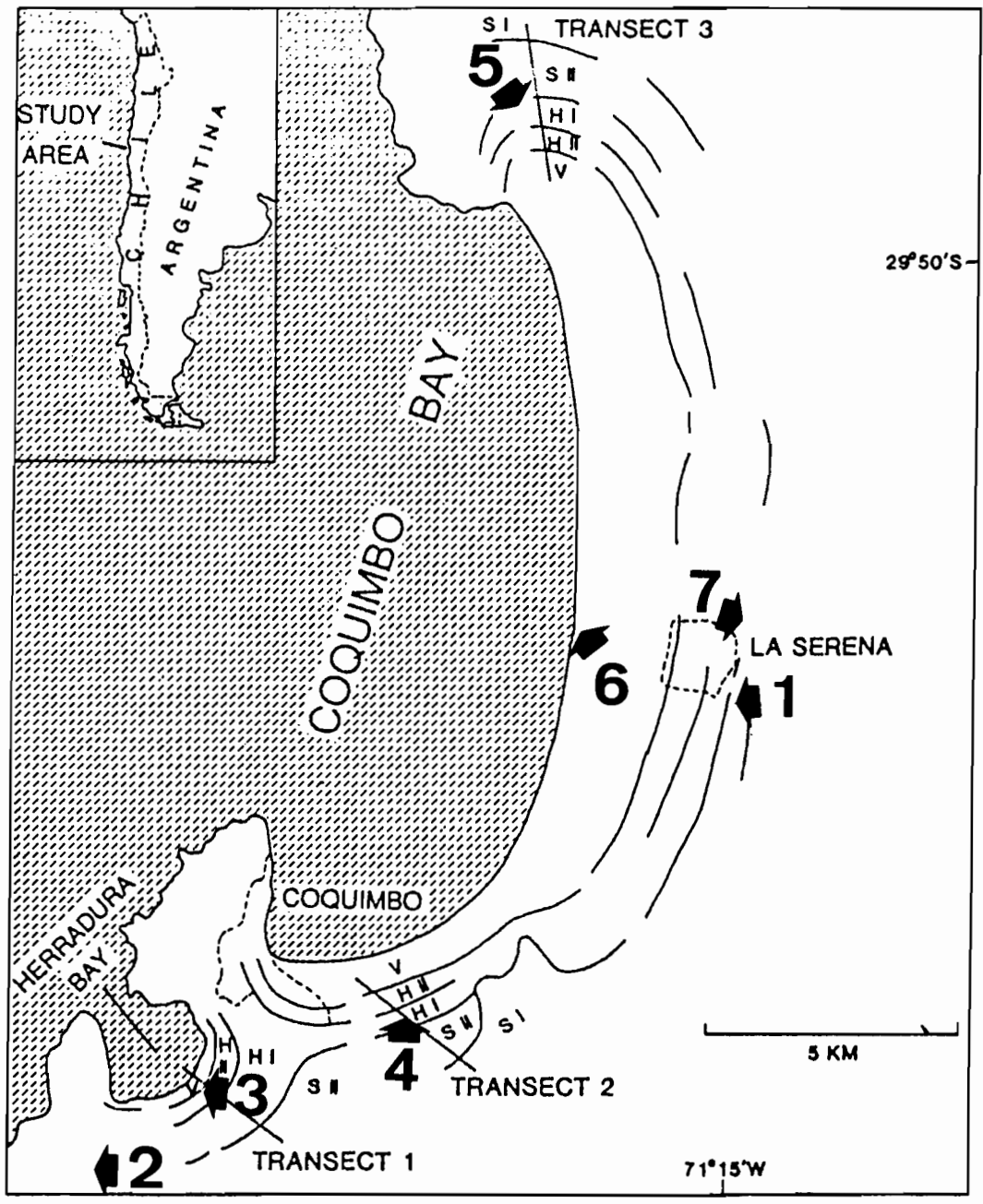


FIGURE 8. The Coquimbo Bay area: field trip stops and transects studied by Leonard and Wehmiller (1992).
 Transect 1 corresponds to Herradura Bay (HB), transect 2 to Cantera Baja (CB), and transect 3 to Punta Teatinos (PT).
 SI: Serena I. SII: Serena II. HI: Herradura I. HII: Herradura II. V: Vega.

Forty-one *Prothotaca* and *Mulinia* valves were analyzed from Coquimbo Bay terrace deposits. *Mulinia* A/I values were converted to “*Prothotaca* equivalent A/I values” using a relationship found by Hsu (1988) in Peru. A/I values were generally consistent within stratigraphic units and increased with terrace altitude, providing support for the use of aminostratigraphy at Coquimbo Bay. Figure 9 plots A/I values (± 1 s) of samples from the Herradura II and Herradura I terraces along all three transects. There appear to be two groups of A/I values of shells on each terrace, groups which are consistent with terrace stratigraphy, except for two shells at one site which appear to have been reworked from an older unit into a younger one. These stratigraphically consistent groups were used to define four “aminozones”, called X, Y1, Y2, and Z, on the low terraces at Coquimbo Bay (table 3).

Aminozone	Mean <i>Prothotaca</i> equivalent A/I	number of shells
X	0.41 \pm 0.04 (1s)	13
Y1	0.60 \pm 0.04 (1s)	8
Y2	0.69 \pm 0.02 (1s)	8
Z	0.84 \pm 0.05 (1s)	7

Table 3. Aminozones in the Coquimbo Bay area

The Herradura II terrace contains shells from aminozones X and Y1, either at different sites or, at Herradura Bay, in vertical superposition at a single site, indicating terrace reoccupation during successive high sea-level stands. Similarly, the Herradura I terrace contains aminozones Y2 and Z shells, either at different sites or, at Punta Teatinos, in the northern part of the Coquimbo Bay, in vertical superposition.

Assignment of approximate numerical ages to terrace deposits was accomplished through application of a kinetic model of epimerization developed for *Prothotaca* in California (Wehmiller *et al.*, 1988; Hsu *et al.*, 1989). The model relates a sample age to its A/I value with an equation of the form:

$$A/I = kt^y$$

where t is sample age. The constants k and y are primarily functions of temperature and genus respectively. Based on A/I values from independently dated deposits in California, a value for y was established and in the past it was assumed that this value was appropriate for Chilean

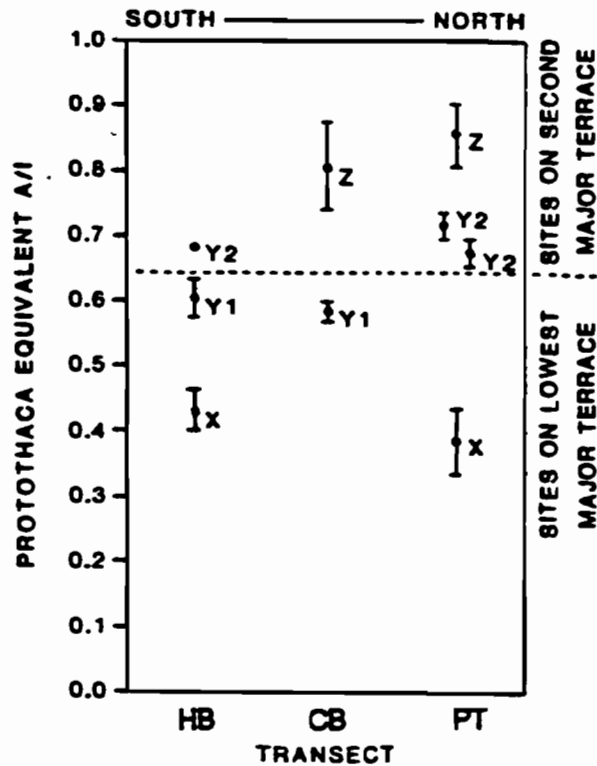


FIGURE 9. *Protothaca* equivalent A/I values for stratigraphic units sampled in the Coquimbo Bay area (modified from Leonard and Wehmiller, 1992).

A/I values are plotted as mean \pm 1 σ . Labels (X, Y1, Y2, and Z) indicate aminozone to which unit is assigned. The lower A/I value aminozone Y2 site on PT transect (transect 3) is on the 49 m intermediate terrace.

HB: Herradura Bay. CB: Cantera Baja. PT: Punta Teatinos.

Protothaca as well. The value of k must be determined for each site from a local calibration, in this case, by electron spin resonance calibration of aminozone X. Recent Th/U dating of solitary coral and amino acid analysis of fossil molluscs from a middle Pleistocene deposit at Morro Copiapó, near Caldera (27°04' S), suggests that the y value developed for *Protothaca* in California may not be appropriate in Chile, and, as a result, that the previously calculated ages may be somewhat too old (Leonard *et al.*, 1994). Table 4 and figure 10 include both the ages based on the California kinetic model and those based on a preliminary Chilean model.

AMINOZONE	CALIFORNIA MODEL			PRELIMINARY CHILEAN MODEL	
	Best Age Estimate (10 ³ yr B.P.)	95% certainty age range (10 ³ yr B.P.)	Probable isotope stage	Best Age Estimate (10 ³ yr B.P.)	Probable isotope stage
Y1	303	242-364	9	ca. 230	7
Y2	413	340-486	11	ca. 290	9
Z	646	552-794	17?	ca. 410	11

Table 4. Numerical age estimates for aminozones in the Coquimbo Bay area

According to E.M. Leonard and J.F. Wehmiller, the two numerical age models suggest the following alternative sequences of events in the Coquimbo Bay area:

Model I - Based on California kinetic model

Herradura I terrace formed *ca.* 650 ky and reoccupied probably during isotope stage 11

Herradura II terrace formed during isotope stage 9 and reoccupied during stage 5

Model II - Based on initial Chilean kinetic model

Herradura I terrace formed during stage 11 and reoccupied during stage 9

Herradura II terrace formed during stage 7 and reoccupied during stage 5

It is interesting to note that neither proposed sequences indicates a stage 7 terrace in the Coquimbo Bay area, confirming a suggestion by U. Radtke (1989). Therefore, the model of simple transgression-regression cycles for the genesis of the wave-cut terraces is incomplete. This evidence for reoccupation supports an hypothesis put forward by U. Radtke (1989) that, as a

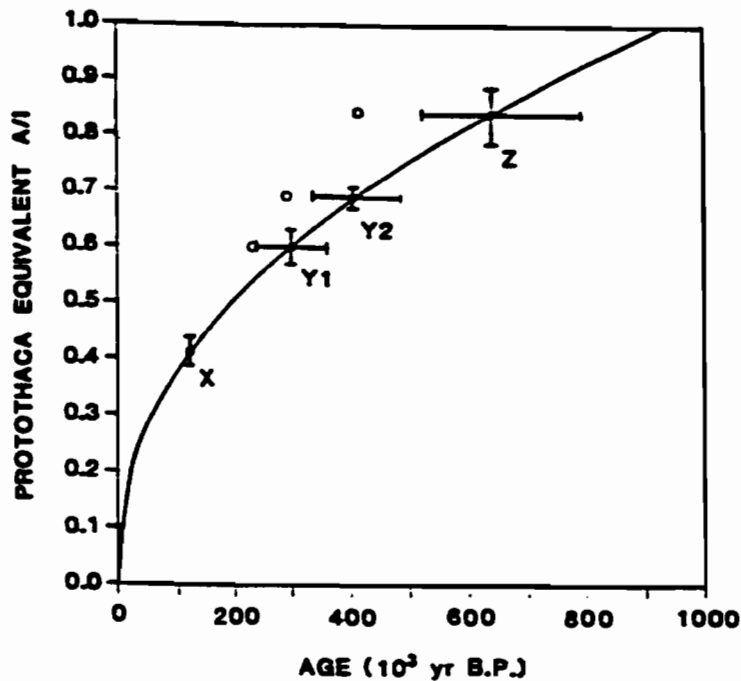


FIGURE 10. Age calibration from aminozones at Coquimbo Bay (modified from Leonard and Wehmiller, 1992).

The best-fit curve is plotted using the California kinetic model and is based on the assumption that aminozone X dates from marine isotope stage 5e. Older aminozones are plotted along the curve based on their mean A/I values. Vertical error bars show 95% confidence range for calculated ages. Open circles show the most probable ages for the older aminozones based on the initial Chilean calibration model. Confidence intervals around these ages have not been yet determined.

result of low uplift rates, the amount of uplift between successive high eustatic sea-level stands may have been insufficient to isolate the abrasion platform formed during one high stand from reoccupation during a subsequent one. It appears that everywhere around the bay, the isotope stage 5 transgression was high enough to reoccupy or overtop any preexisting stage 7 terrace.

Net coastal uplift rates may be calculated if terrace age and the position of eustatic sea-level at the time of terrace formation are known. Using age estimates from table 3 and a eustatic sea-level record for the last 425 ky compiled from several sources (see Leonard and Wehmiller, 1992), uplift rates were calculated for the three above mentioned transects in the Coquimbo Bay area (table 5)

Terrace interval	California Model			Preliminary Chilean Model		
	Time interval (10 ³ yr B.P.)	Uplift (m)	Uplift rate (m/10 ³ yr)	Time interval (10 ³ yr B.P.)	Uplift m	Uplift rate (m/10 ³ yr)
Herradura Bay						
22 m to modern shoreline	125 to 0	16	0.13	125 to 0	16	0.13
41 to 22	425 to 125	25	0.08	320 to 125	21	0.1
Southern Coquimbo Bay						
28 to modern shoreline	320 to 0	24	0.08	211 to 0	39	0.18
Northern Coquimbo bay						
25 m to modern shoreline	125 to 0	19	0.15	125 to 0	19	0.15
58 to 25 m	425 to 125	39	0.13	320 to 125	35	0.18

Table 5. Net uplift rates in the Coquimbo Bay area

Whichever model is used, calculated long-term uplift rates are very low for an active continental margin, as already suggested by R. Paskoff (1977). Such uplift rates, in no case greater than 0.2 m/1000 yr, are substantially lower than those reported for most areas of ocean-continent plate convergence. They may be related to an anomalously low dip segment of the subducted Nazca plate in the Coquimbo area.

Correlating the Herradura II and Herradura I terraces with the 125 ky (stage 5e) and 320 ky (stage 9), respectively, and assuming a constant uplift rate of approximately 0.11m/ky for the Quaternary as a whole, which is rather unlikely since vertical crustal movements have probably been irregular in amplitude and frequency, K. Lajoie (1991) concluded to tentative ages of 730 ky

and 1.2 My for the Serena II and Serena I terraces. However, according to ESR datings obtained by T. Furutani (1995), the age of the Serena I terrace would be about 500 ky (stage 13). As a matter of fact, in this case, the ESR technique is approaching its upper limit and such an age is probably too young. The geomorphic context suggests a Pliocene age for the Serena I terrace.

FIELD TRIP STOPS

Stop 1. University of La Serena, view point overlooking the southern part of the Coquimbo Bay area

Observation of landscape and general geomorphic presentation of the flight of wave-cut terraces on which the city of La Serena developed since its foundation in 1544.

Stop 2. Pan American Highway, going up from Herradura Bay

Large quarry permitting observation of the upper unit of the Coquimbo Formation; examination of strata (sedimentary features and fossils) overlying the granitic bedrock (fig. 11).

Stop 3. Pan American Highway, Herradura Bay

Type locality of the Herradura II terrace (last interglacial) and discussion of its age. Examination of the Vega terrace (Holocene) dated on archaeological and radiocarbon evidence.

A cut of the Pan American Highway gives a good section of the Herradura II terrace (fig. 12, photo. 3). It shows from bottom to top:

- soft yellowish sandstones belonging to the Coquimbo formation (middle to upper Miocene), visible through about 5 m, including an indurated bed, 25 cm thick, made of mollusc molds: *Laevicardium procerum domeykoanum* (PHIL.), *Protothaca petitiana* (D'ORB.), *Panope coquimbensis* D'ORB.;

-erosional unconformity;

- layer of blocks covered by weakly consolidated beach deposits mixing sands, pebbles, and well-preserved shells, about 1,50 m thick; the following species were identified by D. Herm: *Mesodesma donacium* (LAM.), *Mulinia edulis* (KING.), *Tagelus dombeii* (LAM.), *Crepidula dilatata* SOW., *Tegula atra* (LESS.), *Olivia peruviana* (LAM.), all already existing in the

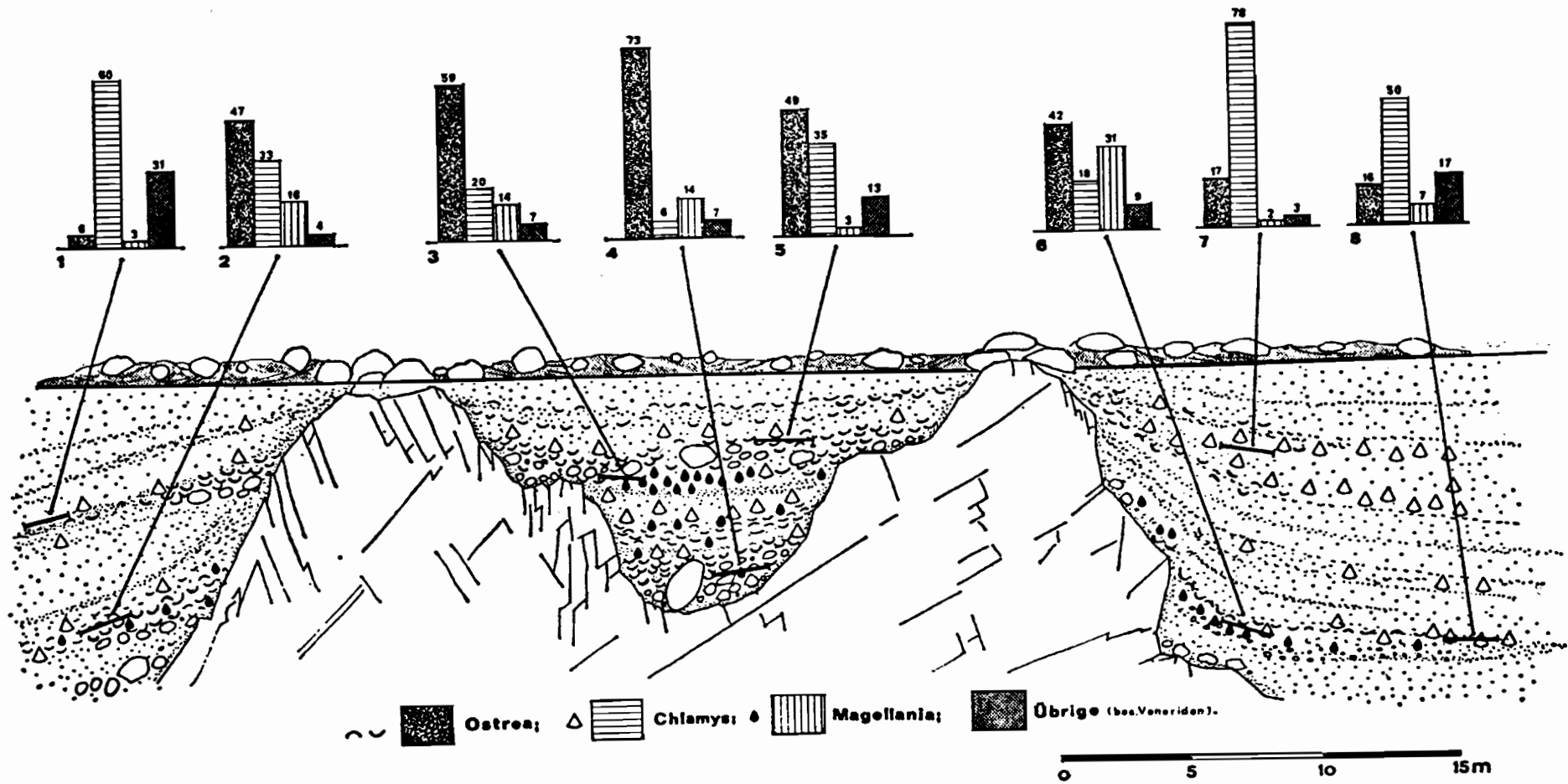


FIGURE 11. Section of the Pan American Highway, just south-west of Herradura Bay, showing fossiliferous upper strata of the Coquimbo Formation burying the granitic bedrock (Herm, 1969).

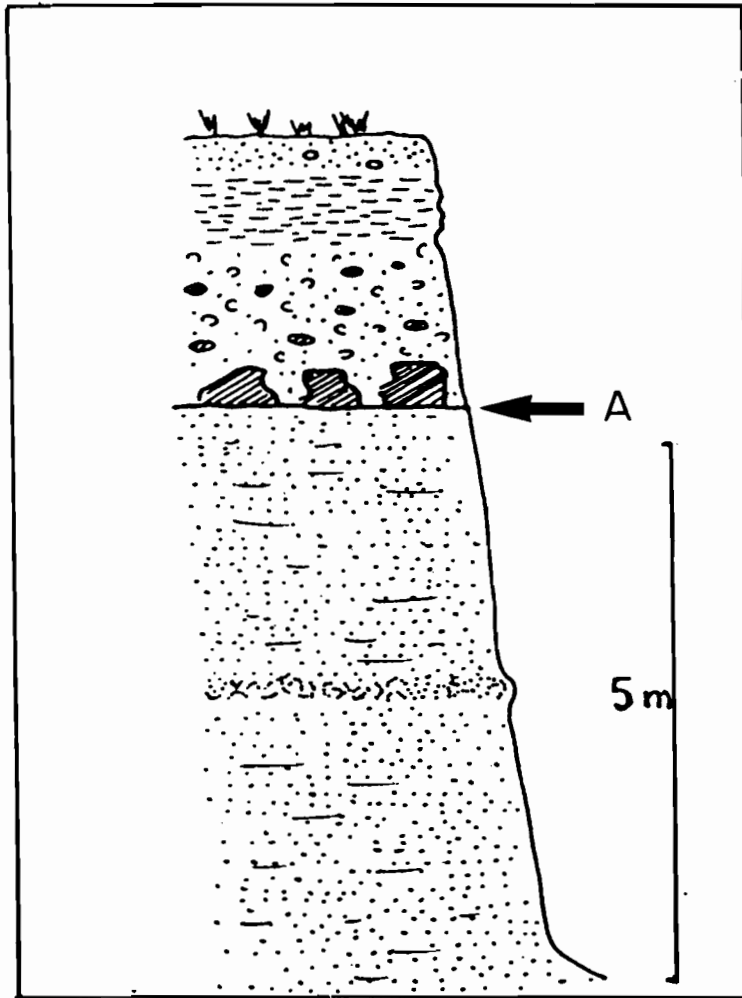


FIGURE 12. Section into the Herradura II terrace at the type locality (Herradura Bay).
A points to an erosional unconformity between the last interglacial beach deposits at the top and the underlying soft sandstones of the Coquimbo Formation ascribed to the middle to upper Miocene (Paskoff, 1970).



PHOTO 3. Section of the Pan American Highway, near Herradura Bay, showing an erosional unconformity (arrow) between middle to upper Miocene sandstones of the Coquimbo Formation and overlying coarse, shelly beach deposits of the last interglacial period, capping the Herradura II terrace (photo. R. Paskoff).

Coquimbo Formation; unknown species in the Coquimbo formation are: *Chlamys purpurata* (LAM.), *Anatina (Raeta) undulata* (GOULD.), *Semele corrugata* (SOW.), *Transennella pannosa* (SOW.), *Protothaca thaca* (MOL.), *Argobuccinum scabrum* (KING.), and *Cantharus* sp.;(see Table 6).

- calcareous crust (70% of Ca CO₃), 0,75 cm thick;
- weakly developed soil with a relatively high humus content (Veit, 1991), 0,25 cm thick.

Height at the top of the section: 18 m.

R. Paskoff and D. Herm (1969) assumed that the Herradura II terrace was last interglacial in age. U. Radtke (1989) agrees with this view. However, the ESR and Th/U datings he obtained from the Herradura II terrace are not internally consistent (fig. 13) and he suggested that older (penultimate interglacial, stage 7 ?) material has been reworked. As a matter of fact, the 200,000 yr high sea-level platform seems to have been completely eroded since the overwhelming majority of datings of the Herradura I terrace in the same area (fig. 13) suggest that it was formed before 200,000 B.P., probably during an older marine transgression (stage 9 ?). A similar opinion is expressed by E.M. Leonard and J.F. Wehmiller (1992). They distinguished two fossiliferous marine units, apparently separated by an unconformity, atop the Herradura II terrace. Nine shells from the upper unit (six *Protothaca* and three *Mulinia*) yielded a mean *Protothaca* equivalent A/I value of 0.43 ± 0.03 (aminozone X), three *Mulinia* shells from the lower unit a mean *Protothaca* equivalent A/I value of 0.60 ± 0.03 (aminozone Y1). This difference in A/I values confirms the presence of a hiatus within the depositional sequence capping the Herradura II terrace. The California kinetic model would suggest a stage 9 age for the lower unit on the terrace, the preliminary Chilean model a stage 7 age. Thus, it appears that the Herradura II terrace was occupied during at least two high stands of sea-level corresponding to stage 5e and probably to stage 7. Such a case of terrace reoccupation is the result of a low local uplift rate, as the amount of uplift between the two successive glacio-eustatic high sea-level stands was not sufficient to put the platform cut during the stage 7 transgression beyond reach of the 5e transgression.

Around Herradura Bay, the lower terrace -the Vega terrace- starts at the present shoreline and extends to a height of about 5 m where it ends at a foot of a dead marine cliff, a few meters high, forming the outer edge of the Herradura II terrace (fig. 14). Prior to radiocarbon datings, this terrace was thought to be of Holocene age on archaeological grounds (Paskoff, 1970). Remnants of the preceramic *Anzuelo de Concha* (hooks made of shells) culture (shell middens dated at ca. 6,000 yr B.P.) are never found on this lower terrace, but only at the top of the abandoned sea cliff limiting the Herradura II terrace (fig. 15). Artifacts and shell middens of the younger El Molle culture (ca. 2,000 yr B.P.) are occasionally located on the lower terrace. Thus,

Terrace Localities:	Herradura II			Herradura I
	C95.236	C95.259	C95.238	C95.235
GASTROPODS :				
<i>Aeneator fontainei</i>				P
<i>Calyptreaea (T.) trochiformis</i>	P	P	A	P
<i>Cancellaria (S.) buccinoides</i>				?
<i>Collisella orbigny</i>			P	
<i>Concholepas concholepas</i>	P	P	P	P
<i>Crassilabrum crassilabrum</i>	P	P	P	
<i>Crepidatella dilatata</i>	A	A	A	
<i>Crepidatella dorsata</i>		P		P
<i>Crucibulum cf. C. lignarium</i>	P		P	
<i>Crucibulum quirinquinae</i>		P		
<i>Diloma nigerrima</i>	?			
<i>Fissurella maxima</i>				?
<i>Mitrella unifasciata</i>	P		P	?
<i>Nassarius dentifer</i>		P		
<i>Nassarius gayi</i>	A	V		V
<i>Oliva (O.) peruviana</i>	A	P	P	V
<i>Polinices (P.) uber</i>			P	P
<i>Priene rude</i>		P	?	P
<i>Priene scabrum</i>	P		P	P
<i>Prisogaster niger</i>		P		A
<i>Tegula (C.) atra</i>				A
<i>Tegula (C.) euryomphala</i>	P	P	P	A
<i>Tegula (C.) luctuosa</i>	P	P	V	P
<i>Turritella cingulata</i>	P	P	P	V
<i>Xanthochorus cassidiformis</i>	A	P	P	A

Table 6. See legend on next page

Terrace Localities:	Herradura II			Herradura I
	C95.236	C95.259	C95.238	C95.235
PELECIPODS :				
<i>Argopecten purpuratus</i>	A	P	A	A
<i>Barbatia pusilla</i>	P			P
<i>Brachidontes granulata</i>		A		
<i>Cardita sp.</i>		P	P	P
<i>Carditella tegulata</i>			P	
<i>Choromytilus chorus</i>	A	P	A	
<i>cf. Clausinella gayi</i>				V
<i>Cryptomya californica</i>	P	A	A	
<i>Diplodonta inconspicua</i>	P	A	P	P
<i>Ensis macha</i>	P	A	P	P
<i>Eurhomalea lenticularis</i>	P	V		V
<i>Eurhomalea rufa</i>		A		V
<i>Glycymeris ovatus</i>				A
<i>Mesodesma donacium</i>	P	P		
<i>Mulinia cf. M. edulis</i>	V	V	P	?
<i>Mysella sp.</i>	P	A	P	
<i>Nucula sp.</i>	P			
<i>Ostrea sp.</i>				V
<i>Perumytilus purpuratus</i>				P
<i>Petricola (P.) rugosa</i>		P		
<i>Pholas (T.) chiloensis</i>	P	P		
<i>Protothaca (P.) thaca</i>	P	P	P	P
<i>Raeta (R.) undulata</i>	P	P	A	
<i>Semele solida</i>	A		P	P
<i>Tagelus dombeii</i>	V	A	A	P
<i>Transennella pannosa</i>	V	A	A	A
<i>Venus antiqua</i>	P		A	P



PHOTO. 4. Large boulder protruding on the surface of the Herradura I terrace, near the Coquimbo railway station (photo. R. Paskoff).

Table 6. Composition of the molluscan fauna of marine terraces Herradura II and Herradura I (determination L. Ortlieb & N. Guzmán). Samples C95-236 and C95-259 correspond to the locality of Stop 3, while sample C95-238 comes from another outcrop of the Herradura II terrace, at Coquimbo (29°57.8' S, 71°19.8'W). Sample C95-235 comes from the Stop 4 locality (Herradura I). Letters mean : P=present; A=abundant; V=Very abundant .

Comparison of the faunal assemblages of the two terraces leads to a series of observations.

First, it must be noted that many species are common in the deposits of both terraces (*Calyptraea trochiformis*, *Concholepas concholepas*, *Crepidatella dorsata*, *Nassarius gayi*, *Oliva peruviana*, *Polinices uber*, *Priene rude*, *P. scabrum*, *Prisogaster niger*, *Tegula euryomphala*, *T. luctuosa*, *Turritella cingulata*, *Xanthochorus cassidiformis*, *Argopecten purpuratus*, *Barbatia pusilla*, *Cardita sp.*, *Diplodonta inconspicua*, *Ensis macha*, *Eurhomalea rufa*, *E. lenticularis*, *Prothaca thaca*, *Semele solida*, *Tagelus dombeii*, *Transenella pannosa*, *Venus antiqua*). It may be added that these common species are also found nowadays in the nearshore area.

Among the differences in the faunal assemblages of Herradura I and Herradura II units, a distinction can be made between the differences assignable to specific palaeo-environmental factors and differences which may be more significant (in terms of variation of distribution ranges). For instance, the presence of *Cryptomya californica* and *Raeta undulata* in the Herradura II deposit must be related to a particular protected lagoon palaeo-environment; in the same way, the occurrence of *Petricola rugosa* and *Pholas chiloensis* in a specific deposit of Herradura II only means that a favourable substrate was present at that locality.

The species which are found in abundant number in the Herradura I deposit and which are lacking in the Herradura II units are: *Tegula atra*, *Clausinella gayi*, *Glycymeris ovatus*, *Ostrea sp.* (cf. *O. columbiensis*). *Ostrea sp.* and *Clausinella gayi* are not extant in the area of Coquimbo. Their absence in Herradura II deposits may imply that their disappearance predates the Herradura II high sea stand.

Species that are abundant in Herradura II units, and which are lacking in the sampled Herradura I locality are the following: *Crepidatella dilatata*, *Brachidontes granulata*, *Choromytilus chorus*, *Cryptomya californica* and *Mulinia* cf. *M. edulis* (?). It is interpreted that these differences are only due to palaeo-ecological differences between the specific sampled localities (not to regional appearance after Herradura I episode).

In conclusion, there are only little differences in the composition of the faunal assemblages between both terrace deposits and between the Herradura I and II episodes and the present fauna. *Ostrea sp.* and *Clausinella gayi* seem to be the only species which disappeared from the area, after the Herradura I episode of high sea-level (the distribution range of *Clausinella gayi* is presently restricted to the Magellanic Province, to the south of Valparaíso).

Finally it may be noted that fossiliferous deposits supposedly contemporaneous of Herradura II and I in the Antofagasta-Hornitos region (see Fieldguide of the first excursion) contains several species that were not found at Coquimbo: *Chione peruviana*, *Cyclinella subquadrata*, *Gari solida*, *Diodora saturnalis*, *Sinum cymba* and *Xanthochorus buxea*. It is inferred that, at the end of the Middle Pleistocene and/or during the last interglacial episode, the southern limit of the distribution range of these species ended somewhere between lat. 24°S and 29° S. On the reverse, *Clausinella gayi* never reached the latitude of the Tropic of Capricorn in the Pleistocene.

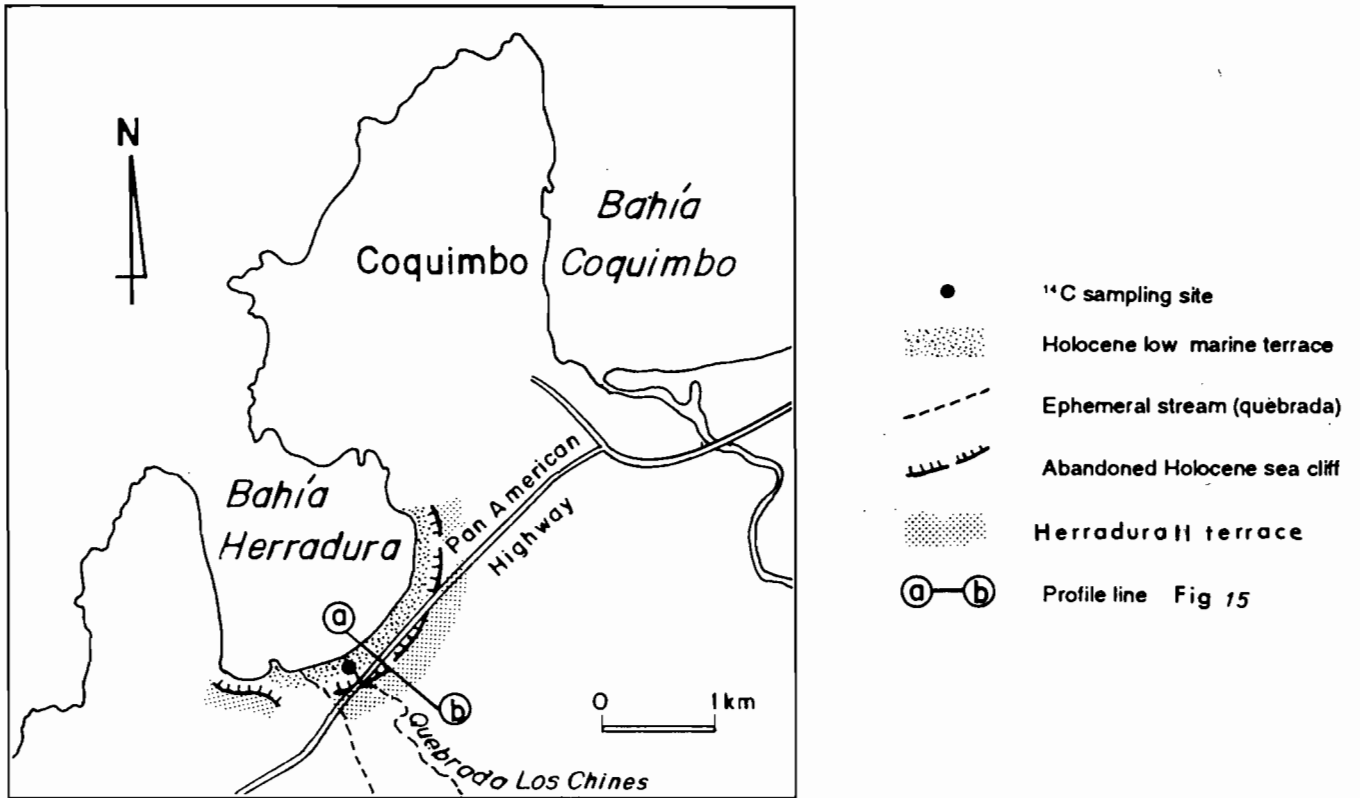


FIGURE 14. The Holocene marine terrace (Vega terrace), at Herradura Bay.

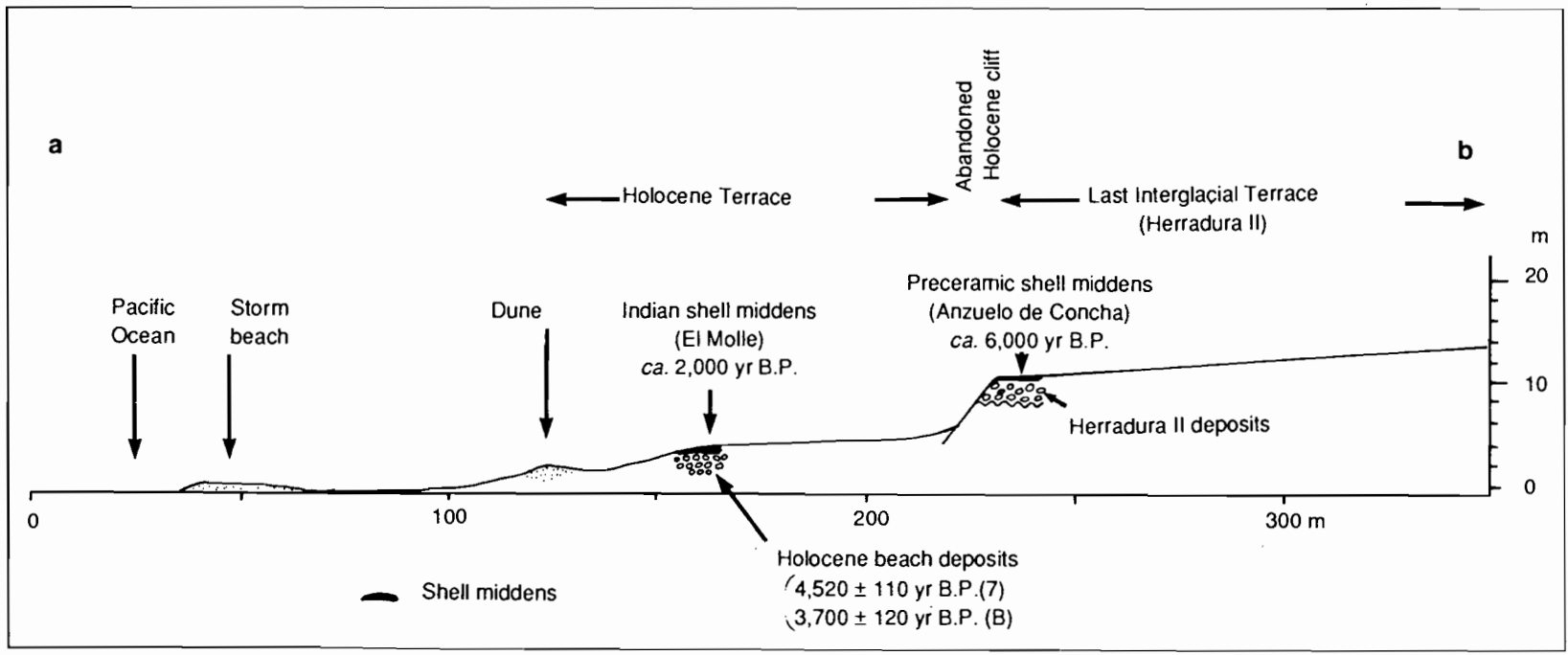


FIGURE 15. Profile across the Holocene and Herradura II terraces, showing locations of archaeological remnants, at Herradura Bay (Ota and Pakoff, 1993).

it was logical to assume that the lower terrace was submerged and the cliff still active at *ca.* 6,000 yr B.P., but had emerged by *ca.* 2,000 yr. B.P. when the El Molle people settled on it. Several radiocarbon datings on shells collected from deposits capping the lower terrace have since confirmed the Holocene age previously assumed for this level: 3,700±120 yr B.P. (Paskoff, 1973), 4,090 (Radtke, 1989), 4,520±110 yr. B.P. (Ota and Paskoff, 1993).

Stop 4. Cantera Baja road, east of Coquimbo

Observation of large boulders on the Herradura I terrace and discussion of the megatsunami hypothesis for their deposition.

At this place, only two *Protothaca* shells were analyzed by E.M. Leonard and J.F. Wehmiller (1992) and yielded a mean A/I value of 0.80±0.7, which may indicate a correlation with aminozone Y2. In this case, the terrace would have been formed during isotope stage 9, according to the preliminary Chilean kinetic model. No ESR ages are available for this terrace. However, we may reasonably assume an age of about 300,000 yr B.P. for it.

Here, the terrace is notable because of the occurrence of scattered large boulders which are embedded in the shelly beach deposits associated with the abrasion platform. The source of the boulders is known on the basis of their distribution and their petrographic nature. They came from the Coquimbo peninsula (fig. 16). Some are of medium to fine-grained monzonite or tonalite. Others are of andesite or diabase. Such kinds of rocks are not found on the coastal slopes which limit Herradura Bay inland. They outcrop in the Coquimbo peninsula which is characterized from a geological point of view by a Jurassic to lower Cretaceous granitic intrusion cut by thick volcanic dykes.

The boulders, which can be more than 2 m in length (photo. 4), present a problem. They were transported over long distances, sometimes exceeding 2 km, from the rocky Coquimbo peninsula that still was an island when the Herradura I terrace developed. They were deposited under marine coastal waters, they are included in stratified beach deposits (photo. 5), they are covered by shells, and in some cases they have barnacles adhering to them. Therefore, they constitute integral elements of the terrace deposits. It is puzzling to think how boulders of such size could have been transported and dropped where they now lie. The boulders are beyond the power of normal waves or currents to carry them over a long distance from their source on the slopes of the former Coquimbo peninsula

It must also be pointed out that the episode of boulder deposition was unique since their occurrence in the area is limited to a single terrace. A few boulders of similar size and composition found on the surface of the Herradura II terrace must be considered as lag boulders. Exceeding the competency of normal waves, they remained *in situ*, but at a lower elevation, during the subsequent marine transgressions which are responsible for the genesis of the Herradura II platform. The phenomenon of boulder deposition was never repeated. Therefore, it must be considered as an exceptional event which resulted from very rare and unusual conditions.

B. Willis (1929), who was the first to recognize these boulders and the impossibility of their transportation by ordinary waves and currents, suggested that they were floated. Two agents for this peculiar mode of transport, which could account for the distribution of boulders, may be imagined. One consists of rafts of tree trunks carrying large rocks in their roots. The other is ice. No field evidence for either has been found. B. Willis discarded as highly improbable the existence in the area of trees sufficiently large to transport such boulders. He also thought that it would be unreasonable to postulate any development of huge masses of ice in a subtropical latitude, even during a glacial period of the Pleistocene. However, he presumed that, at the time of formation of the Herradura I terrace on which the boulders are scattered, the local climate could have been severe enough to permit some coastal ice to form in shady areas of limited extension and in sufficient volume to afford local transportation of large blocks. He also assumed that they were derived from a rock gorge cut into the pre-Tertiary basement by a small stream, the Estero Culebrón. This point of view is hard to accept since the marine terrace bearing the boulders developed during a phase of high sea-level corresponding to an interglacial period, by no means propitious to ice formation in a latitude of 30°.

An alternative explanation which does not demand an unrealistic assumption was proposed by R. Paskoff (1991). Because the Pacific coast of South America is today episodically affected by tsunamis, it is most probable that the large boulders were displaced by powerful waves generated by an earthquake of exceptional magnitude. Their distribution points to waves which came from the north-west. They moved large blocks when passing over the rocky island of Coquimbo and spread them over the nearshore of that time. This unusual tsunami was a unique event since, as evidenced by the occurrence of boulders on a single terrace, it happens only once in Plio-Quaternary times, probably around 300,000 years ago. Discussion from the participants of the trip about this mega-tsunami hypothesis is strongly encouraged.

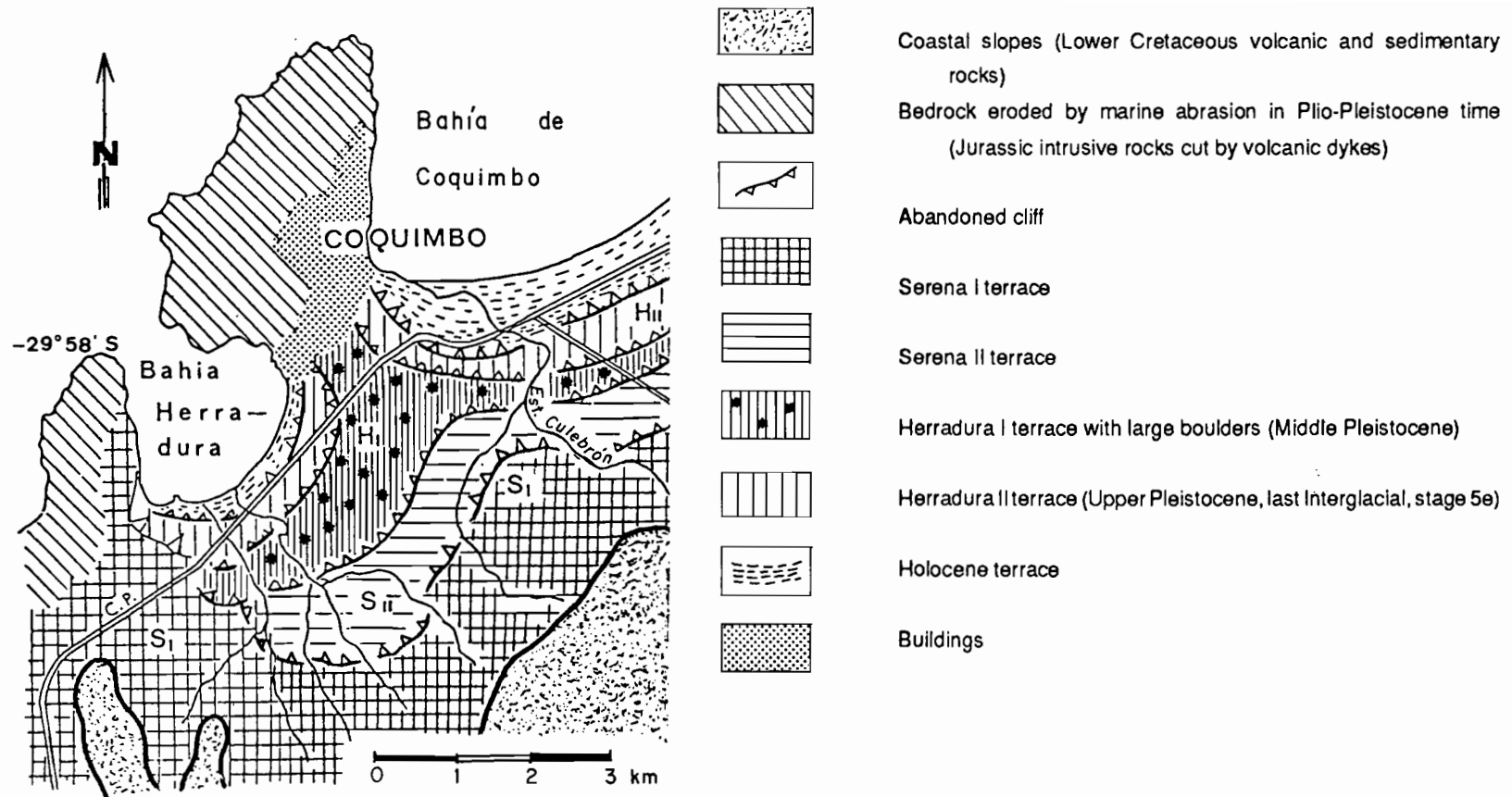


FIGURE 16. Distribution of large boulders on the Herradura II terrace, south-east of Coquimbo (Paskoff, 1991).

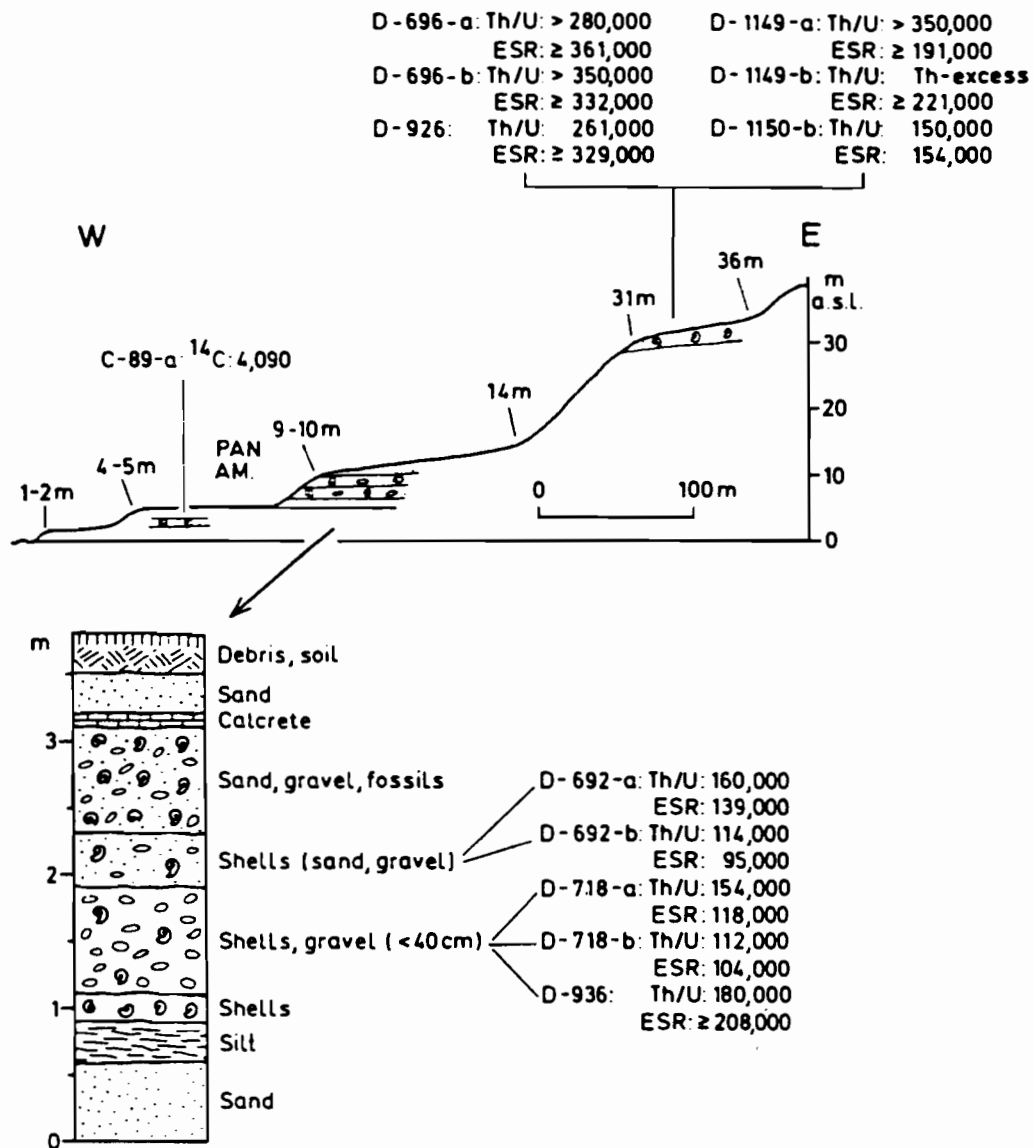


FIGURE 13. Th/U and ESR datings from the Herradura I and Herradura II terraces, and radiocarbon dating from the Vega terrace, at Herradura Bay (Radtke, 1989).



PHOTO 5. Large boulder buried in beach deposits of the Herradura I terrace, near Cantera Alta, east of Coquimbo (photo. R. Paskoff).

Stop 5. Pan American Highway, Punta Teatinos, north end of Coquimbo bay

Examination of a sequence of six step-like wave-cut platforms and associated beach deposits (fig. 17).

At the north end of Coquimbo Bay, in the surroundings of Punta Teatinos, a series of terrace deposits is exposed in cuts of the Pan American Highway. The two higher terraces are entirely cut onto upper Cretaceous to lower Tertiary crystalline rocks. The highest one, the so-called *Llano Porotitos* (flat level capped by “peas” which obviously are small, well-rounded, marine water-worn gravels) may have been formed when the Miocene transgression was approaching its culmination. The Serena II terrace was cut, partly onto crystalline rocks, partly onto soft sandstones of the Coquimbo Formation. Only the Herradura I and Herradura II terraces, with shoreline angle altitudes of 58 m and 25 m respectively, are overlain by sediments rich in fossils. Such altitudes indicate that the northern part of the Coquimbo Bay area has been somewhat more uplifted than the southern part. An inconspicuous scarp at about 49 m, noticed by E.M. Leonard and J.F. Wehmiller (1992), may indicate the upper edge of a possible intermediate terrace not mentioned in figure 17.

Figures 18 and 19 along with table 2 give Th/U and ESR datings obtained by U. Radtke (1989) for the Herradura II and Herradura I terraces. A mean *Protothaca* equivalent A/I value of 0.38 ± 0.05 (aminozone X) for the Herradura II terrace (photo. 6) was derived from two *Protothaca* and two *Mulinia* samples (Leonard and Wehmiller, 1992). ESR datings from this terrace range from 96,000 to 125,000, indicating an isotope stage 5 age. In calibration of E.M. Leonard and J.F. Wehmiller’s kinetic models, an age of $125,000 \pm 5,000$ yr B.P. is assumed for this Herradura II terrace.

Stratigraphy of sediments capping the Herradura I terrace is complex (fig. 20). Channel cuts a meter or more deep in the upper and lower portions of the section indicate some fluvial reworking. Carbonate fracture fills and possible rhizomorphs extend downward into the sand unit immediately below the base of unit C suggesting an interval of subaerial exposure and possible soil formation preceding the deposition of that unit. Analysis of samples from both above and below the base of unit C also indicates an unconformity at that level. Three *Protothaca* from unit B yielded a mean A/I value of 0.86 ± 0.06 (aminozone Z). In units C and D there appears to be a mixed population of shells. Most shells had aminozone Y2 ratios (mean A/I value = 0.71 ± 0.02), but two had higher ratios, equivalent to those of the unit below. It is probable that these high-ratio shells were reworked from unit B into the overlying younger material. Therefore, the amino acid ratios from the Herradura I terrace fall at least in two groups, indicating that at least two ages of

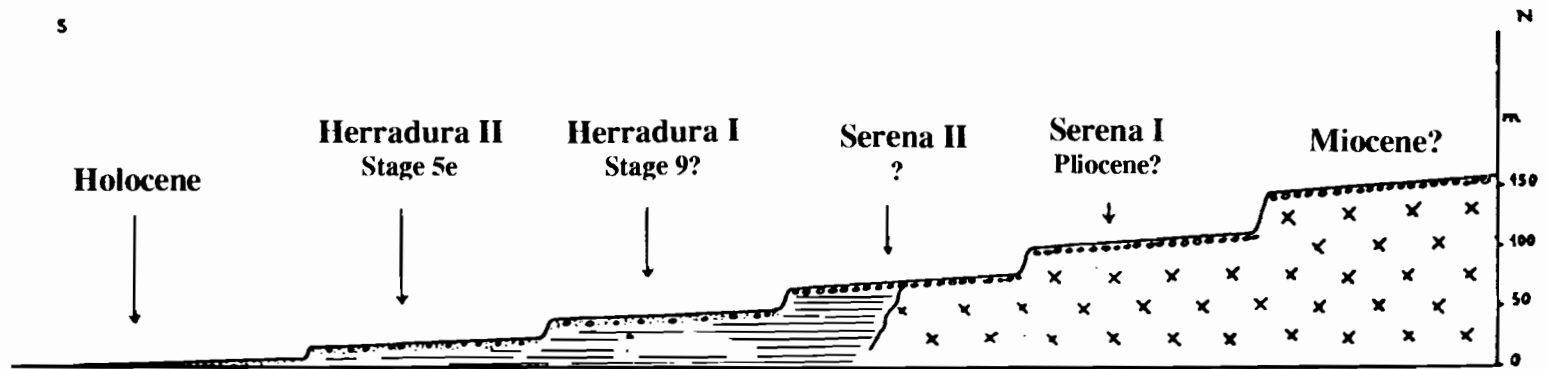


FIGURE 17. Cross-section showing the marine terraces in the northern part of the Coquimbo Bay area (modified from Paskoff, 1970).

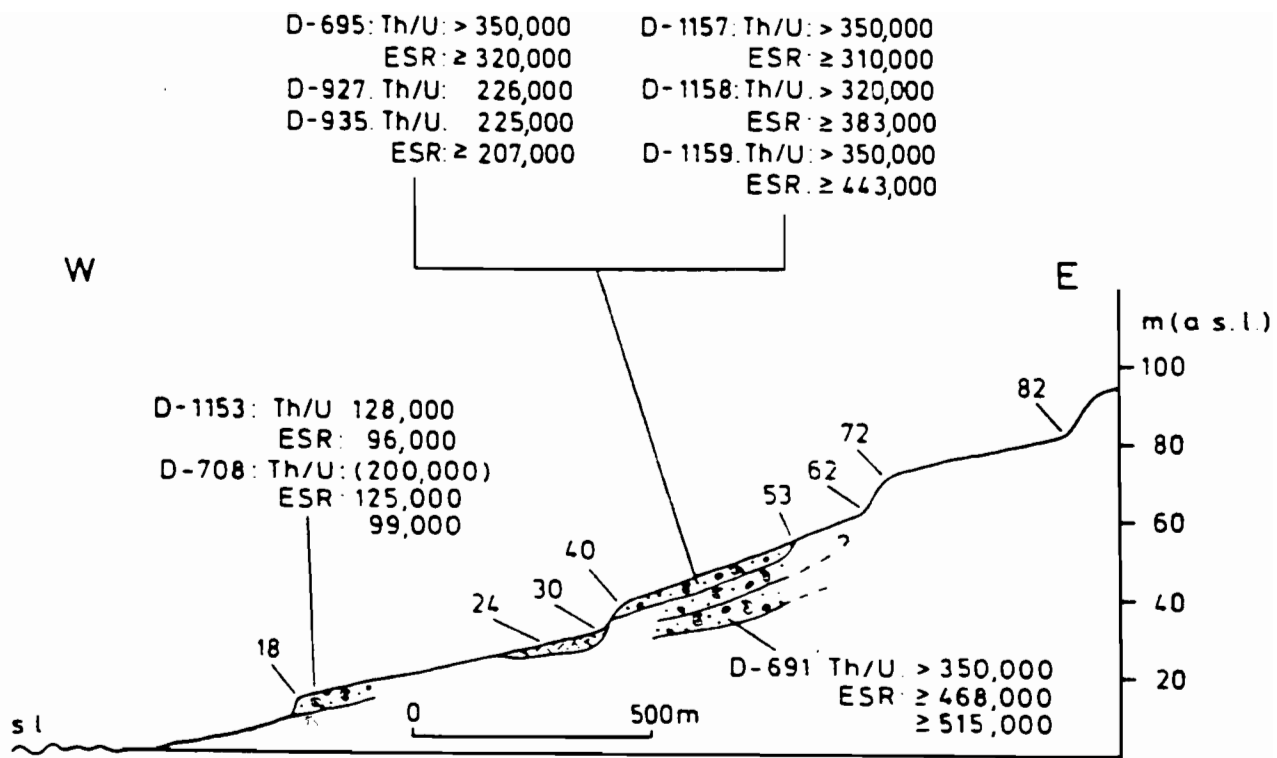


FIGURE 18. Th/U and ESR datings from the Herradura I and Herradura II terraces near Punta Teatinos, in the northern part of Coquimbo Bay (Radtke, 1989).

(1) D-695-a Th/U \geq 350 000	(2) D-706-a Th/U: Th-excess	(3) D-691-a Th/U: \geq 350.000
ESR \geq 320 000	ESR: \geq 276 000	ESR: \geq 455.000
D-695-b ESR \geq 278 000	706-b ESR: \geq 358 000	D-691-b ESR: \geq 547.000
D-777-a ESR \geq 367 000	D-1159-a Th/U: \geq 350 000	D-1160-a ESR: \geq 316.000
D-927 Th/U 226 000	ESR: \geq 449 000	D-1160-b ESR: \geq 271 000
ESR (\geq) 206 000	1159-b Th/U: \geq 350 000	D-1161-a ESR: \geq 360 000
D-935-a Th/U 225 000	ESR \geq 325 000	D-1161-b ESR: \geq 325 000
ESR \geq 234 000		
D-935-b ESR 189 000		
D-1158-a Th/U \geq 320 000		
ESR \geq 335 000		
D-1158-b ESR \geq 368 000		

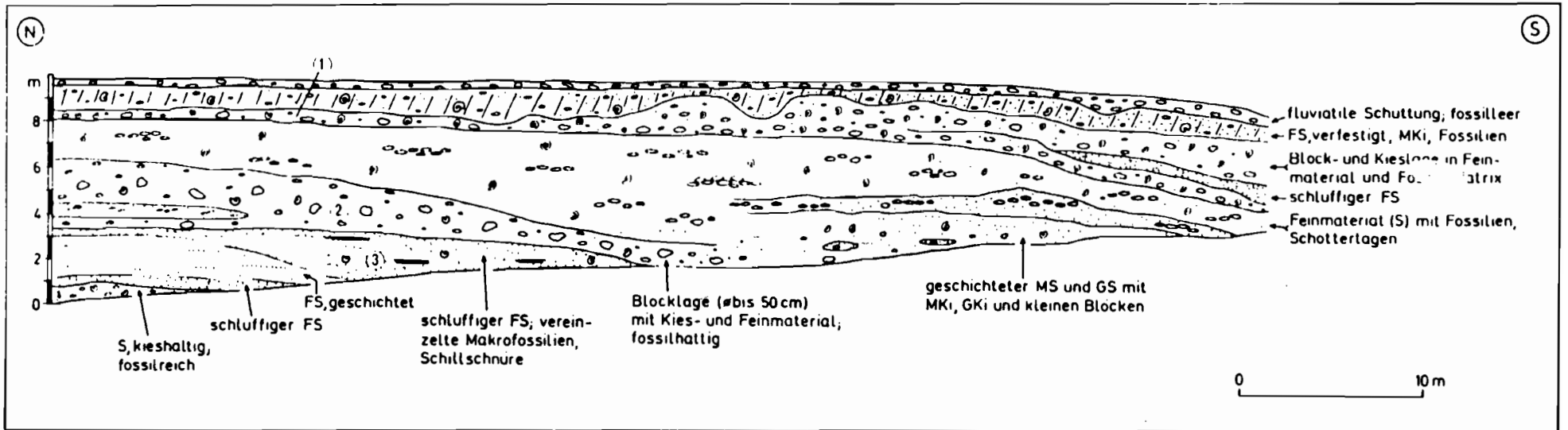


Figure 19. Stratigraphy and datings (Th/U and ESR) of beach deposits on the Herradura I terrace, Quebrada Angostura-Quebrada El Romeral, northern part of Coquimbo Bay (Radtke, 1989).

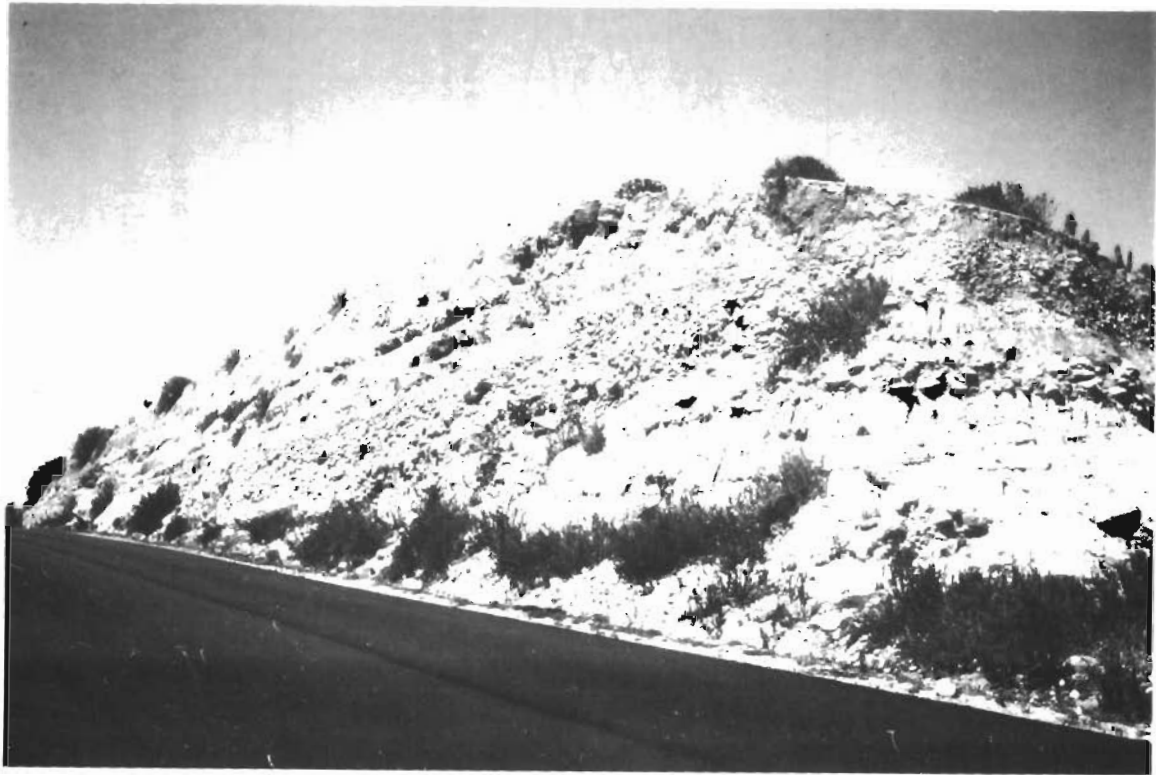


PHOTO 6. Beach fossiliferous deposits, including lenses of continental gravels, on the Herradura II terrace, as exposed in the Pan American Highway cut near Punta Teatinos, at the northern end of Coquimbo Bay (photo R. Paskoff).

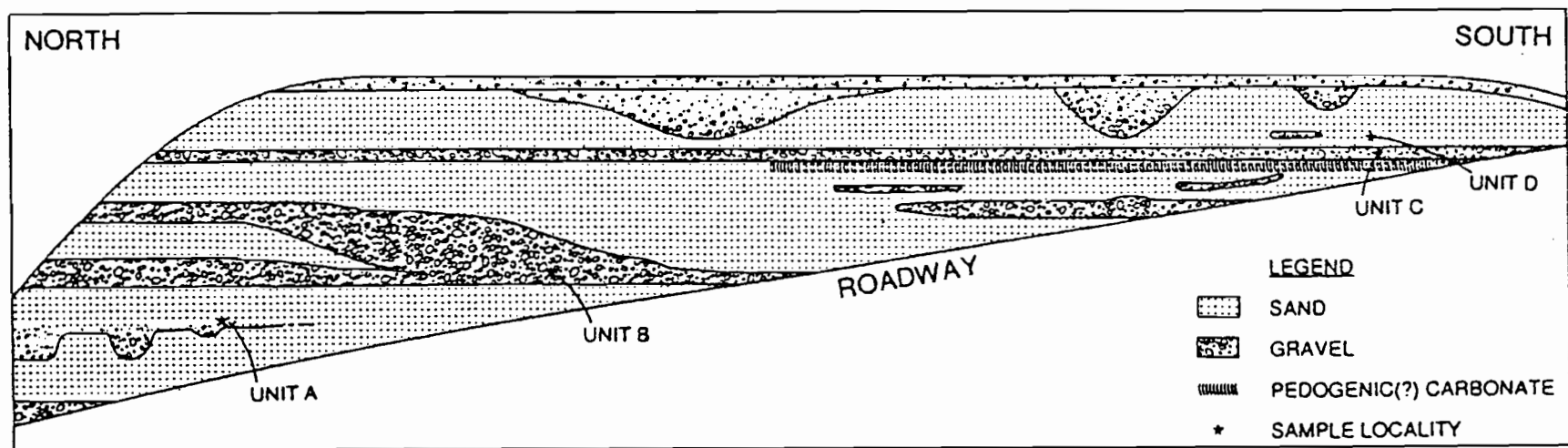


FIGURE 20. Stratigraphy of beach deposits on the Herradura I terrace as exposed in the Pan American Highway cut (km 480), near Punta Teatinos, northern part of Coquimbo Bay. Section was not measured in detail, so thicknesses are only approximate. It is approximately 150 m long and a maximum of 12 m high. Vertical exaggeration is about 2 to 1 (Leonard and Wehmiller, 1992).

shells are present. ESR datings from sediments capping the Herradura I terrace also led U. Radtke (1989) to suggest the possibility of an unconformity below unit C. This unconformity had already been recognized by R. Paskoff (1970), but it was interpreted as an unconformity between transgressive deposits and regressive ones within a single glacio-eustatic cycle. The ESR ages are somewhat difficult to interpret, as nearly all are minimum ages and there is considerable overlap of ages between units. Based on the oldest minimum ages in each unit, however, U. Radtke suggested a break between the deposition of units B and C, at the same stratigraphic level at which E.M. Leonard and J.F. Wehmiller indicate an unconformity on the basis of amino acid data and possible pedogenic carbonates. The alternative kinetic models proposed by E.M. Leonard and J.F. Wehmiller suggest that units above and below the unconformity date from isotope stages 11 and 17 ? respectively using the California calibration, or 9 and 11 using the preliminary Chilean calibration.

List of fossils (determination by D. Herm)

Upper unit: *Balanus laevis* (BRÜG.), *Mesodesma donacium* (LAM.), *Tagelus dombeii* (LAM.), *Chlamys purpurata* (LAM.), *Mulinia edulis* (KING.), *Ameghinomya antiqua* (KING.), *Eurhomalea* cf. *rufa* (LAM.), *Ocenebra* cf. *buxea* (BROD.), *Xanthochorus* cf. *cassidiformis* (BLAINVILLE), *Oliva peruviana* (LAM.) and *Turritella cingulata* SOW.

Lower unit: *Balanus psittacus* (MOL.), *Nucella (Acanthina) acuminata* (SOW.), *Nucella (Acanthina) crassilabrum* (LAM.), *Glycymeris ovata* (BROD.), *Laevicardium procerum grande* (PHIL.) and *Turritella cingulata* (SOW.); the last two species have never been found in the Coquimbo Formation.

Miocene (Coquimbo Formation, lower unit): *Balanus psittacus* (MOL.), *Glycymeris ovata* (BROD.), *Nucella (Acanthina) calcar* (MART.), *A. crassilabrum* (LAM.), *Arcopsis* cf. *solida* (SOW.), *Chlamys coquimbensis* (MÖR.) and *Monoceros pyrulatus* PHIL. The last three species are distinctive of the Miocene Coquimbo Formation.

The inconspicuous scarp, which at about 49 m marks the upper edge of a possible terrace intermediate between the Herradura II and Herradura I terraces, appears to have marine sediments draped over it. It may be a remnant of a cliff perhaps developed during the regression which followed the formation of the Herradura II terrace. Three shells from this intermediate terrace yielded a mean *Protothaca* equivalent A/I value of 0.67 ± 0.02 , indicating an age slightly younger than that of the youngest sediments on the Herradura I terrace, consistent with an interpretation that the beach sediments were deposited during the regression from the Herradura I terrace (Leonard and Wehmiller, 1992).

Stop 6. La Serena, Avenida del Mar

En años recientes, se produjo un desarrollo urbano denso a lo largo de la playa que bordea la Bahía de Coquimbo entre Peñuelas y el faro de La Serena, en los casi 5 km de la Avenida del Mar (foto. 7). Existen ambiciosos proyectos para prolongarla al norte hasta Punta Teatinos y favorecer la urbanización de la franja costera con planes turístico-residenciales. Sin embargo, se han escuchado voces de alerta ante los riesgos y peligros que representan para los asentamientos humanos los maremotos o tsunamis que suelen ocurrir en la Bahía de Coquimbo (Novoa *et al.*, en prensa).

La probabilidad de ocurrencia de tsunamis en la Bahía de Coquimbo se fundamenta en un registro de 37 fenómenos de este tipo desde 1562. En los últimos treinta años, cinco tsunamis (1964, 1975, 1985, 1987, 1988) afectaron esta costa. Una carta de riesgos y peligros por tsunamis en el área intercomunal La Serena-Coquimbo, establecida por J.E. Novoa *et al.*, está incorporada a esta guía. Estos autores introducen una diferencia entre riesgo y peligro. Una situación de riesgo se entiende cuando un fenómeno natural afecta a sectores sin ocupación humana permanente (cultivos, carreteras, caminos, áreas de recreación). El concepto de peligro dice relación esencialmente con sectores urbanizados ocupados en forma permanente, implicando por lo tanto pérdidas potenciales de vidas humanas. Esta clasificación de riesgo y/o peligro presenta tres grados en función de las alturas alcanzadas por las olas de los tsunamis: alto para terrenos ubicados entre 0 y 1,25 m, medio para terrenos ubicados entre 1,25 a 5 m y bajo para terrenos ubicados entre 5 y 15 m.

Diferentes métodos fueron aplicados en el estudio: altura alcanzada por el tsunami en función de la isóbata de 100 m; elevación sobre el nivel medio del mar en función de la pendiente de la bahía; criterio de inundación basado en un modelo usado en Hawai. La probabilidad de ocurrencia de un tsunami de grado 3.0 es de una vez cada 61 años. En este caso, la altura potencial de inundación en tierra alcanzaría hasta los 10 m s.n.m.

En situación de riesgo o peligro alto alrededor de la Bahía de Coquimbo se encuentran 272 y 48 hectáreas, respectivamente. El área sujeta a la condición de riesgo y peligro medio alcanza a 879 y 113 hectáreas, respectivamente. Finalmente, sectores de riesgo y peligro bajo cubren una superficie de 1137 y 198 hectáreas respectivamente. En total, la Bahía de Coquimbo se caracteriza por presentar una superficie de 2647 hectáreas sujetas a inundaciones por tsunamis, sobre las cuales se encuentra una población permanente del orden de 7000 personas a las cuales se agregan unos 5000 visitantes durante el verano.



PHOTO. 7. La Avenida del Mar en La Serena, Bahía de Coquimbo (foto. R. Paskoff).
Urbanización costera densa amenazada por el riesgo de tsunami y la erosión de la
playa.

La tendencia regresiva de las playas ubicadas al sur de la desembocadura del Río Elqui representa otra amenaza para la ocupación turística (Novoa, 1991). En el balneario de Peñuelas, la velocidad del retroceso de la línea de costa, calculada en un período de 24 años, es del orden de 1 m por año (fig. 21). Las causas de esta erosión todavía no han sido claramente establecidas. Al contrario, al norte de la desembocadura del Río Elqui, la costa se caracteriza por una progradación.

Hasta ahora los ambiciosos proyectos inmobiliarios de desarrollo turístico de la Bahía de Coquimbo no han tomado en cuenta los riesgos de inundación y de erosión que tarde o temprano plantearán serios problemas a los promotores de la Avenida del Mar.

Stop 7. (time permitting) La Serena, Regimiento Arica

High point overlooking the fluvial terraces of the lower course of the Elqui river.
Explanation of their formation.

The lower course of the Elqui River is characterized by well-developed stepped terraces (fig. 22, photo. 8.). Four paired levels are clearly noticeable (tI, tII, tIII, tIV, in an order of increasing age) above the present flood-plain.

Results of exploratory drillings for ground-water investigations show that the terraces are the result of a complex history (Paskoff, 1970; figs 23 and 24): (1) deep excavation of the valley in relation to a sea-level well below the present one at the beginning of the Miocene, following the main andean uplift which probably took place at the end of the Oligocene; (2) depositional stage, triggered by a rising sea-level from the middle to upper Miocene and marked by a thick aggradation of continental gravels (Limarí Formation and Elqui Formation, the latter grading with the marine Coquimbo Formation near the mouth of the river); (3) in Plio-Quaternary times, in relation to an oscillating sea-level and a slow uplift of the continental margin, repeated episodes of river entrenchment during regressive periods and lateral planation accompanied by relatively thin alluvial deposition during transgressive periods and high stands of the base level. The result is a flight of stepped and paired fluvial terraces whose surficial gravelly deposits laterally merge with the beach deposits capping the marine terraces observed around Coquimbo Bay (Cooke, 1964). The tI fluvial terrace corresponds to the Vega marine terrace, the tII fluvial terrace to the Herradura II marine terrace, the tIII fluvial terrace to the Serena II marine terrace,

CAMBIOS RECIENTES EN LINEA LITORAL

Bahía de Coquimbo (Chile semiárido)

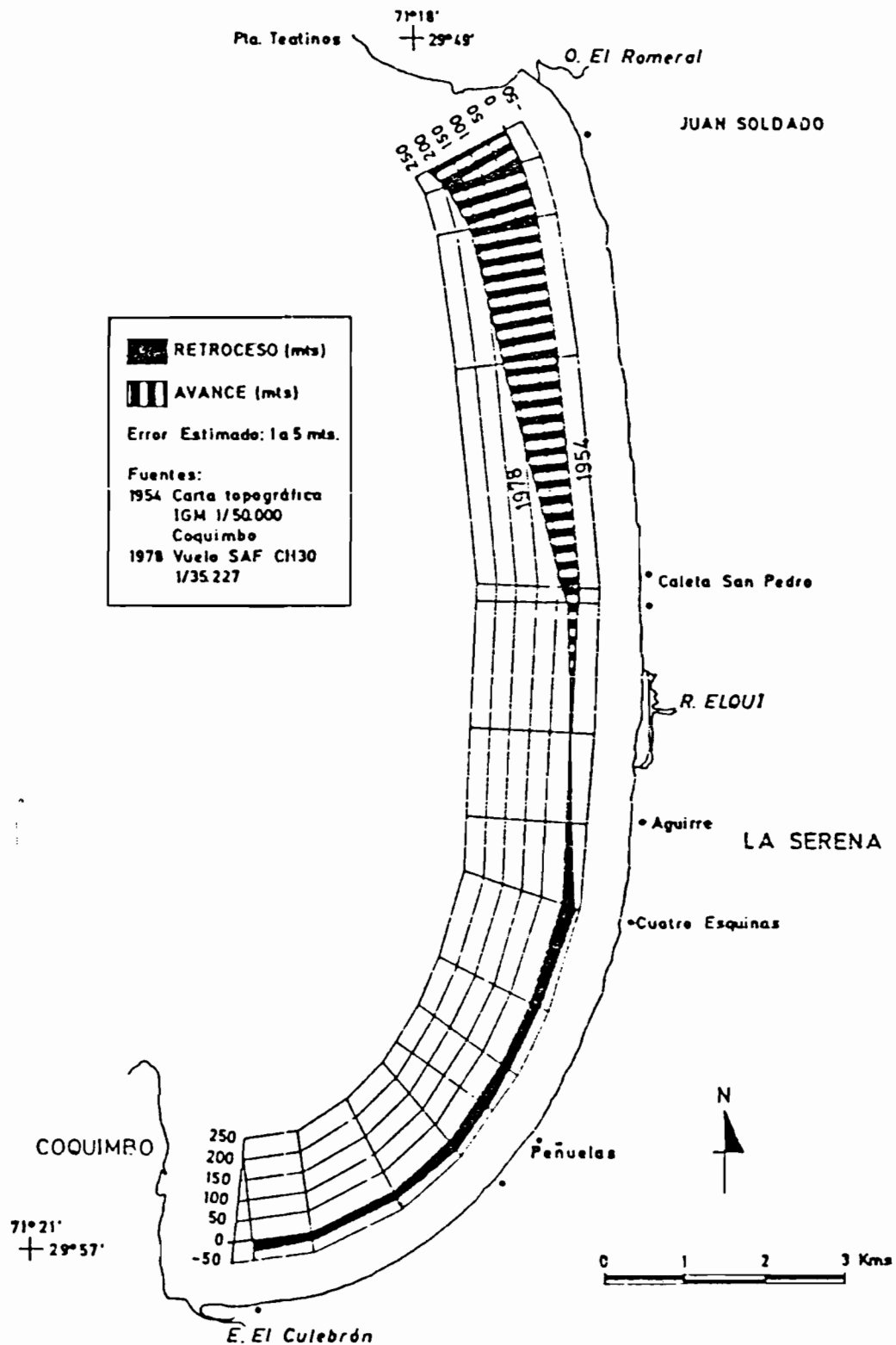


FIGURE 21. Tendencia evolutiva de la línea de costa en la Bahía de Coquimbo durante el periodo 1954-1978 (Novoa, 1991).

Erosión de las playas al sur de la desembocadura del Río Elqui, progradación al norte.

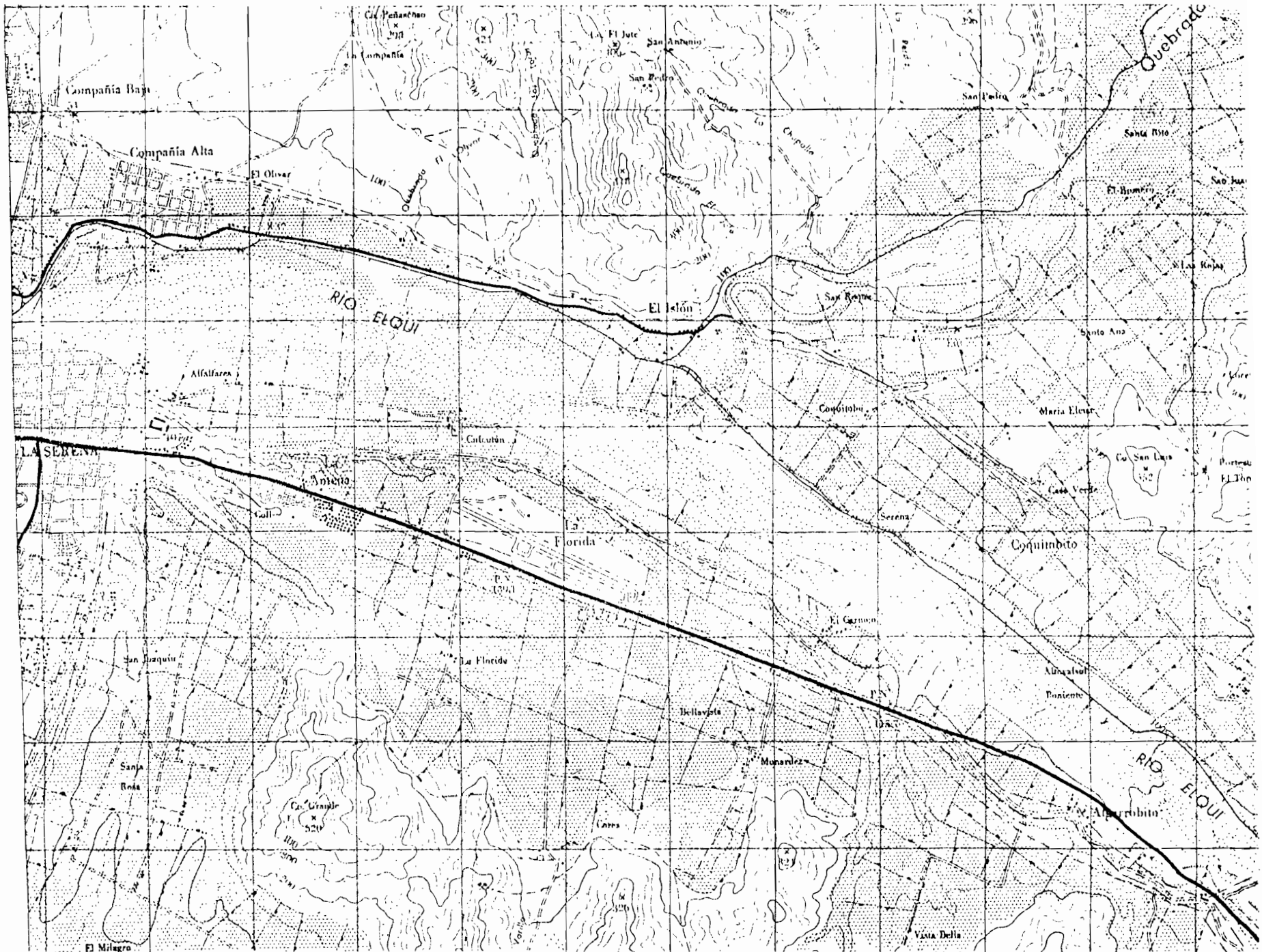


FIGURE 22 . Extract of the 1:50 000 topographic map La Serena showing paired terraces of the Elqui River (I, II, III, IV, in an order of increasing age) above the present flood-plain, near the mouth of the river.



PHOTO 8 . Eastward view of the tII terrace and the bluff marking the edge of the tIV terrace on the south bank of the Elqui River, near La Serena (photo. R. Paskoff).

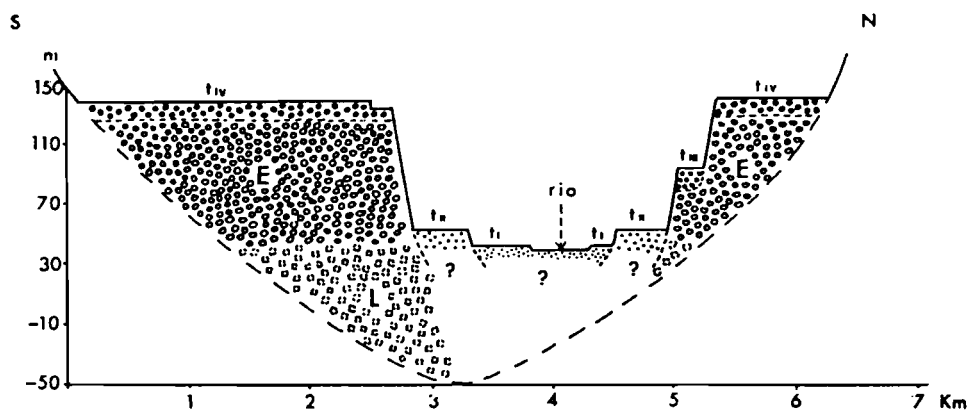


FIGURE 23. Interpretative section across the terraces of the Elqui River near La Serena (Paskoff, 1970).
 L: Limarí Formation. E: Elqui Formation.

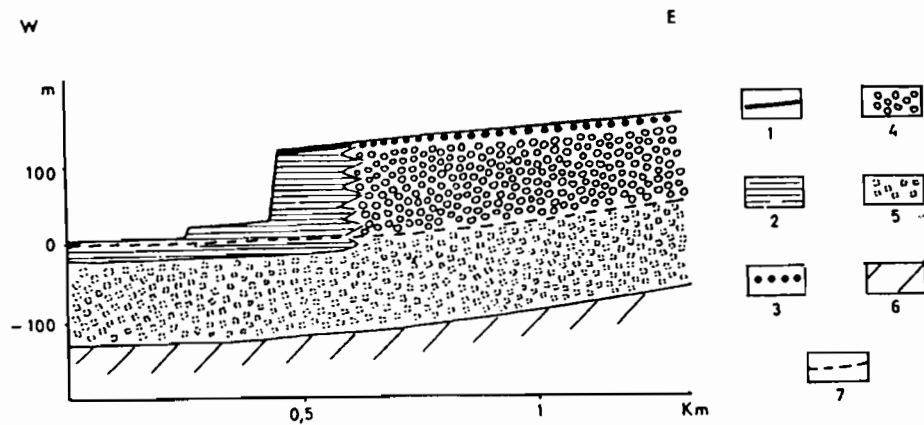


FIGURE 24. Longitudinal interpretative section near the mouth of the Elqui River (Paskoff, 1970).

1: Serena I marine deposits(Pliocene?). 2: marine sandstones of the Coquimbo Formation (middle to upper Miocene). 3: tIV continental gravels. 4: continental gravels of the Elqui Formation (middle to upper Miocene). 5: continental gravels of the Limarí Formation (lower to middle Miocene). 6: bedrock. 7: present thalweg.

the tIV fluvial terrace to the Serena I marine terrace. Only is missing a fluvial terrace corresponding to the Herradura I marine terrace. It has probably been removed by river erosion.

The base level control is valid only for the fluvial terraces which characterize the lower course of the Elqui River. Up-stream, terraces are controlled by climatic conditions. In the High Cordillera headwaters of the Elqui River, moraines and tills pertaining to several generations have been identified and fluvial terraces related to glacial advances have been mapped in the upper and the middle course of the river (Paskoff, 1970).

Stop 8. Quebrada del Teniente, Pan American Highway

Presentation of an uplifted and faulted extensive wave-cut platform.

Contrasting with the surroundings of Coquimbo Bay, the coastal belt of the Talinay Heights (30°15'-31°10' S) corresponds to Plio-Quaternary wave-cut terraces which have been strongly uplifted (fig. 25). The highest marine platform which forms narrow and flat summits reaches about 670 m in the central part of the Talinay Heights (fig. 26). These heights, formed mainly by Paleozoic rocks intruded by Jurassic granitoids, constitute a major structural and geomorphic uplifted unit separated eastward by the north-south trending Puerto Aldea Fault from a graben which starts at Tongoy Bay. This graben was partially filled up by continental gravels brought in by an ancestor of the Limarí River in the lower Miocene (Limarí Formation). It was subsequently partially invaded during the middle to upper Miocene by a transgression, already recognized in the Coquimbo Bay area, whose sediments (Coquimbo Formation) interfinger southward with continental gravels (Elqui Formation). As in Coquimbo Bay, a flight of step-like marine terraces are found around Tongoy Bay. The Serena I, which is especially well-developed and reaches an elevation of *ca.* 200 m, was also cut onto sandstones of the Coquimbo formation and gravels of the Elqui Formation, and merges with the highest fluvial terrace (tIV) of the Limarí River. Such a situation indicates that the Limarí River once flowed towards Tongoy Bay. Subsequently, it changed its outlet and it is now running straight westward to the Pacific Ocean through a deep gorge cut across the Talinay Heights. R. Paskoff (1970) tried to unravel the complicate recent history of the Limarí River (fig. 27) which is directly related to the probably post-Pliocene faulting, tilting and uplifting of the Serena I wave-cut platform and the associated tIV fluvial terrace (fig. 28). A 1:250,000 scale colour map (Paskoff, 1970), which is included in the guide-book, shows the regional distribution of marine platforms, fluvial terraces, and main faults of the area.

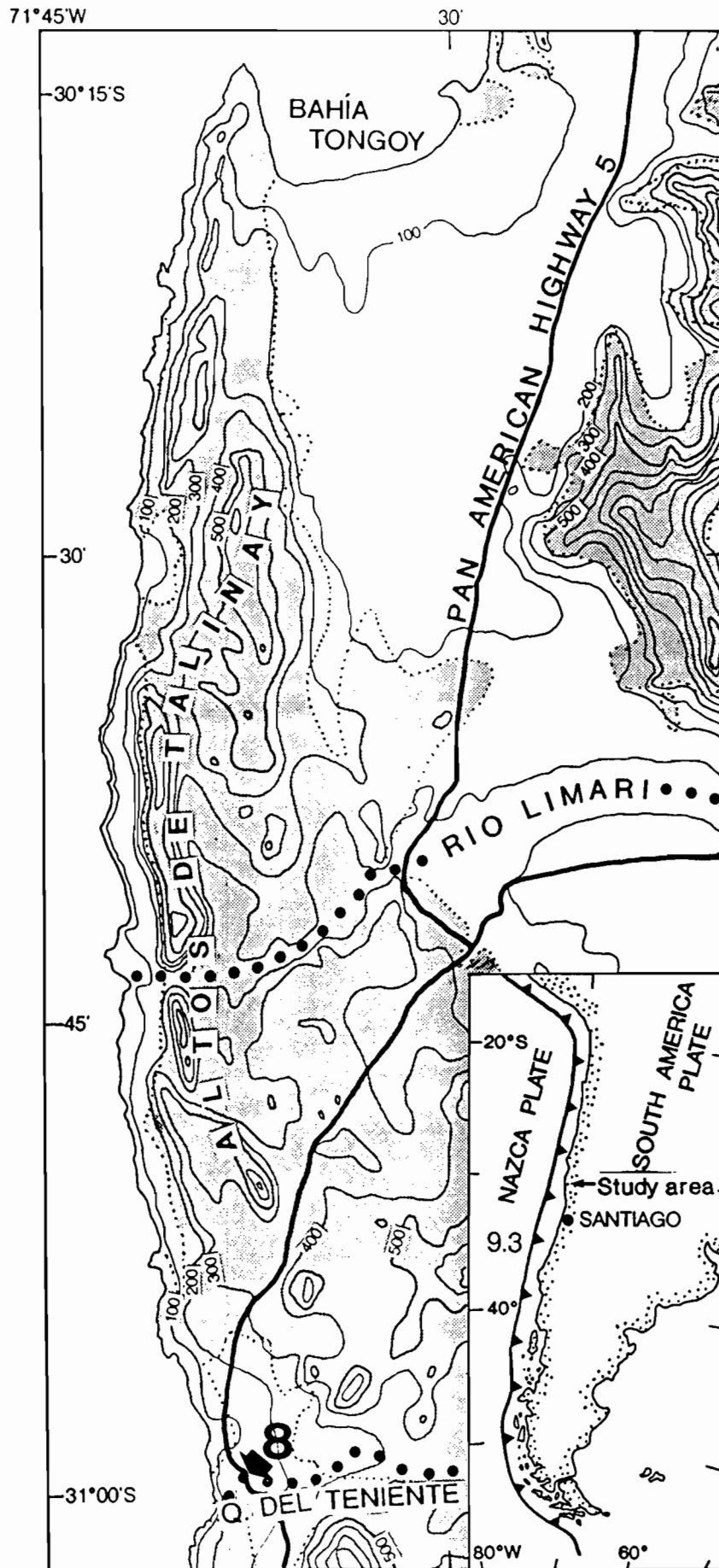


FIGURE 25. Map showing the regional setting of the Talinay Heights and the location of stop 8. Contours represent general topography with 100 m interval. Shaded area indicates the areas underlain by pre-Tertiary rocks.

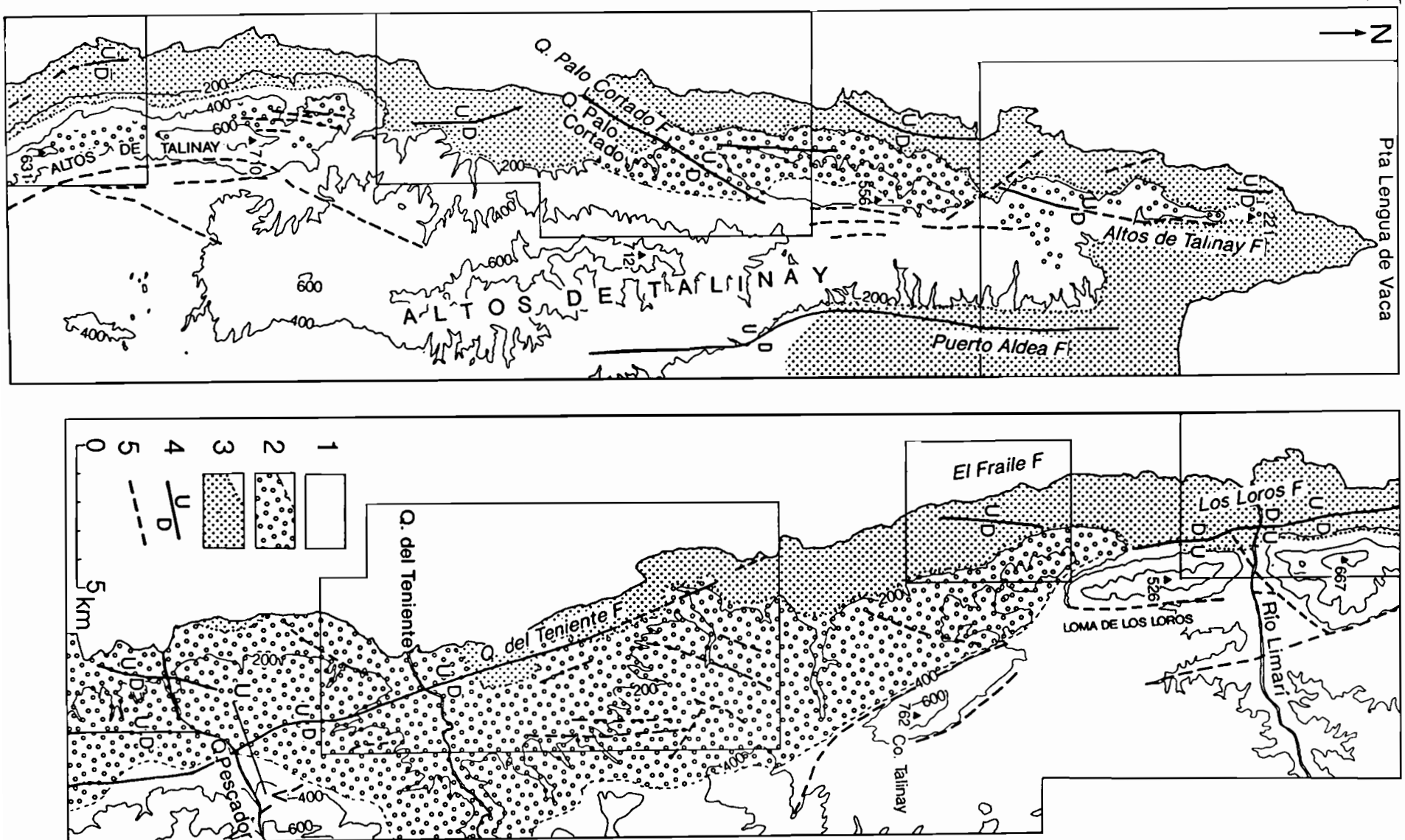


FIGURE 26. Map showing distribution of marine terraces and faults in the Talinay Heights area (Ota, Miyauchi, Paskoff and Koba, 1995).

1: hills. 2: Talinay I shoreline and area covered by Talinay I terrace (Serena I ?). 3: Talinay II shoreline and area covered by Talinay II, III, and IV terraces. 4: Quaternary faults. 5: prominent lineament. Contour interval: 100 m.

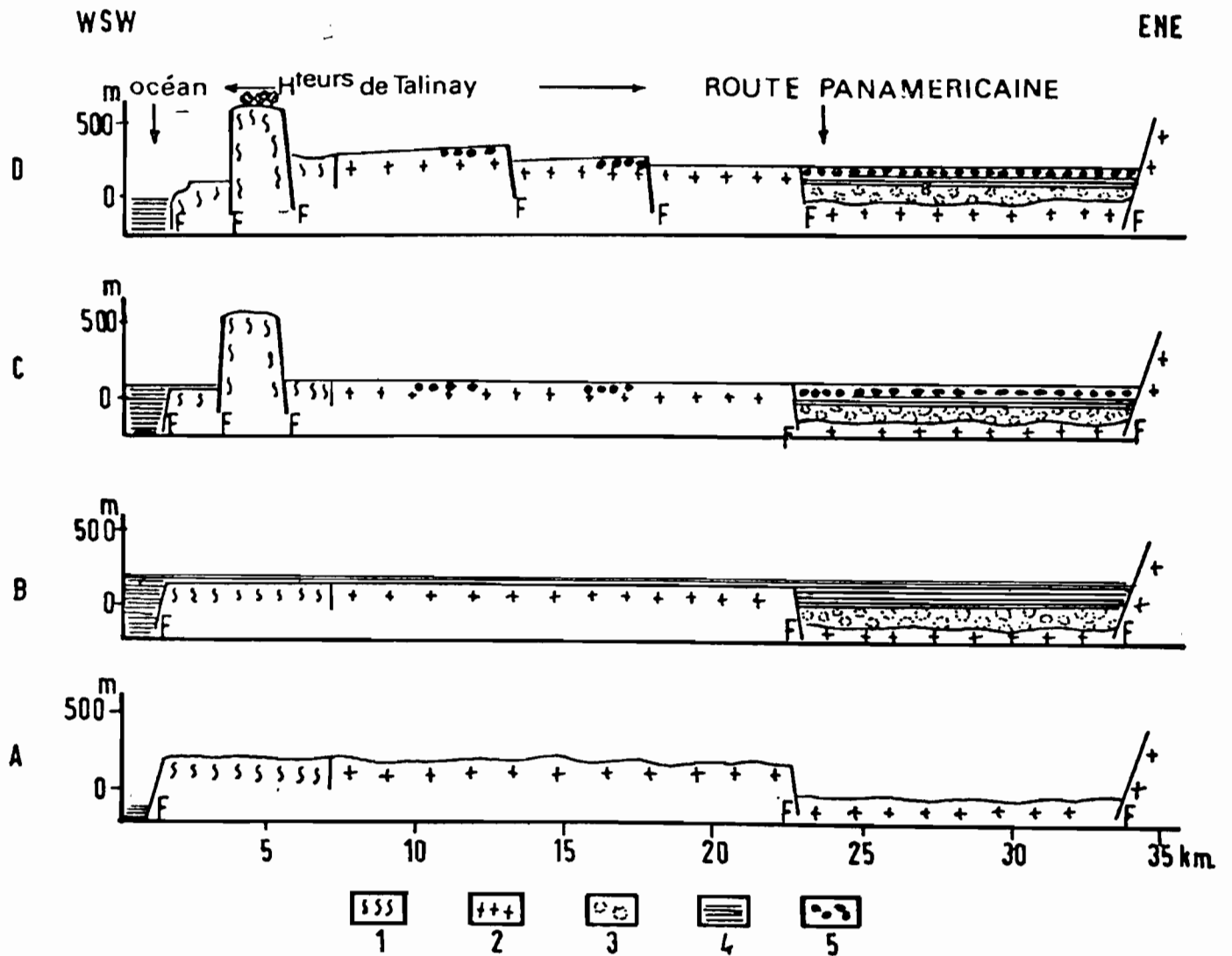


FIGURE 27. Assumed stages in the formation of the Talinay Heights (Paskoff, 1970).

A: lower Miocene. B: upper Miocene. C: Pliocene. D: Quaternary.

1. Paleozoic metamorphic rocks. 2: Jurassic granitic rocks. 3: gravels of the Limarí Formation (lower Miocene). 4: marine deposits of the Coquimbo Formation (middle to upper Miocene). 5: gravels of the tIV fluvial terrace of the Limarí River (probably Pliocene).



PHOTO. 9. Westward oblique aerial picture showing an uplifted extensive wave-cut platform of *rasa* type. In the foreground, the platform has a height of 350-400 m above present sea-level. The long entrenched *quebrada* at the center of the picture is the Quebrada del Teniente. The Quebrada del Teniente fault runs parallel to the coast near the mouth of the ephemeral stream (photo IGM, Chile).

The Quebrada del Teniente area is characterized by the extensive development of a wave-cut platform of *rasa* type (Talinay I terrace in the classification of Ota, Miyauchi, Paskoff and Koba, 1995). This platform (photo. 9), which probably is Serena I in age (Pliocene ?), is cut onto Jurassic intrusive rocks and is covered by a discontinuous veneer of well-rounded pebbles of indisputable marine origin. It ranges in height from 350 to 400 m a.s.l. and may be divided into two or three inconspicuous levels. South of Quebrada del Teniente, the seaward gradient of this very wide terrace becomes steeper toward the west, implying the possibility of a westward downwarping. In this area (fig. 29), the height of the Talinay II terrace (Serena II ?) is from 100 to 120 m a.s.l.; Talinay III (Herradura I ?) is at a height of *ca.* 40-50 m a.s.l. ; Talinay IV (probably Herradura II) is at about 20 m a.s.l.. South of the mouth of Quebrada del Teniente, sand dunes are developed on the marine terraces, making the identification of the terrace morphology difficult.

The distinctively straight NNW-SSE trending Quebrada del Teniente Fault crosses the entire area and it continues southward, reaching about 60 km in length. This fault is one of the most significant faults in the Talinay Heights region (Paskoff, 1970). The Quebrada del Teniente Fault dislocates the Talinay I terrace over most of its trace and, locally, it also displaces the Talinay II terrace, forming an east-facing fault scarp (fig. 30). The amount of vertical displacement on the Talinay I terrace is 40 m at Profile U-V, 44 m at Profile S-T, and reaches its maximum amount of 52 m at Profile Q-R. Displacement decreases northward to only 26 m at Profile O-P, and no displacement is observed at Location 4, although a straight lineament is still clearly traced. This fault dislocates Talinay II terrace northward. An east-facing scarp, 1 m high, is visible at Location 7 (Profile M-N). Here, beach deposits, 1 m thick, on the abrasion platform are exposed on the western upthrown side, and only slope-wash deposits are seen on the downthrown side, suggesting that the actual amount of dip-slip is more than 1 m. Fault exposures are seen at Location 5 and 6. A shattered zone 10 m wide within Paleozoic metamorphic rock, with a fault plane striking N 10° W, dipping 50° E, is exposed on the right wall of a small *quebrada* at Location 6. The strike of this fault plane coincides with that of the Quebrada del Teniente Fault. A blue-grey colored shattered zone is well expressed by its color in a small quarry, although there is no surface displacement (Ota, Miyauchi, Paskoff and Koba, 1995).

At Location 8, near the mouth of Quebrada del Teniente, left-lateral strike-slip of about 1 km has been reported (Paskoff, 1970), based on the offset of a scarp cutting the Talinay I terrace. This offset, however, seems only apparent because: (1) left-lateral offset cannot be seen anywhere else along this fault; (2) upper Tertiary marine deposits (probably Coquimbo Formation) are exposed on the downthrown side of the fault. Therefore, it is likely that this

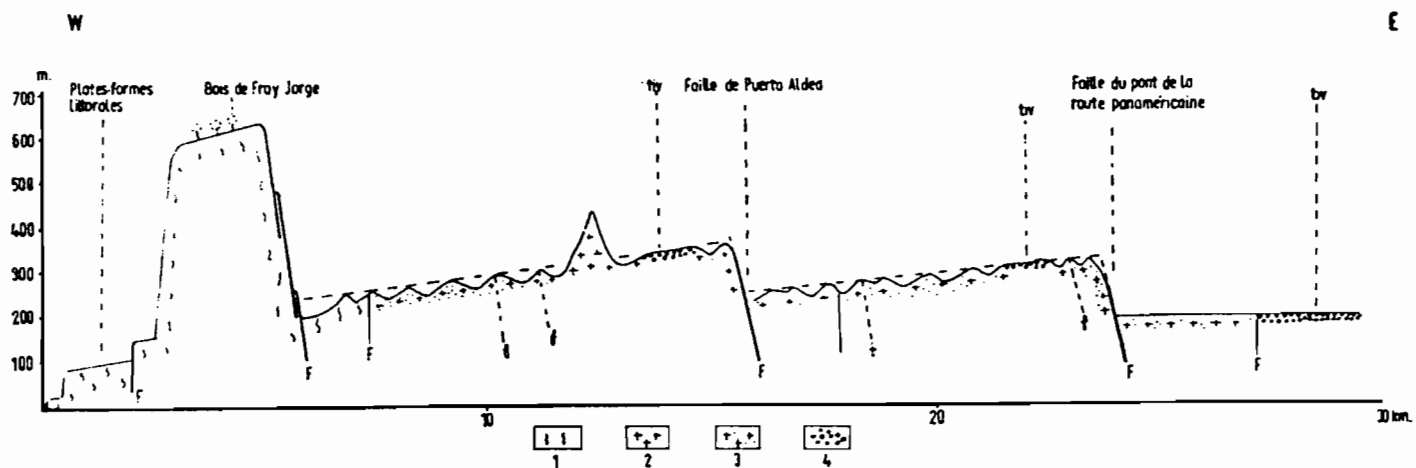


FIGURE 28. Section across the Talinay Heights (Paskoff, 1970).

1: Paleozoic metamorphic rocks. 2: Jurassic granitic rocks 3: weathered Jurassic granitic rocks. 4: gravels of the tIV fluvial terrace of the Limarí River.

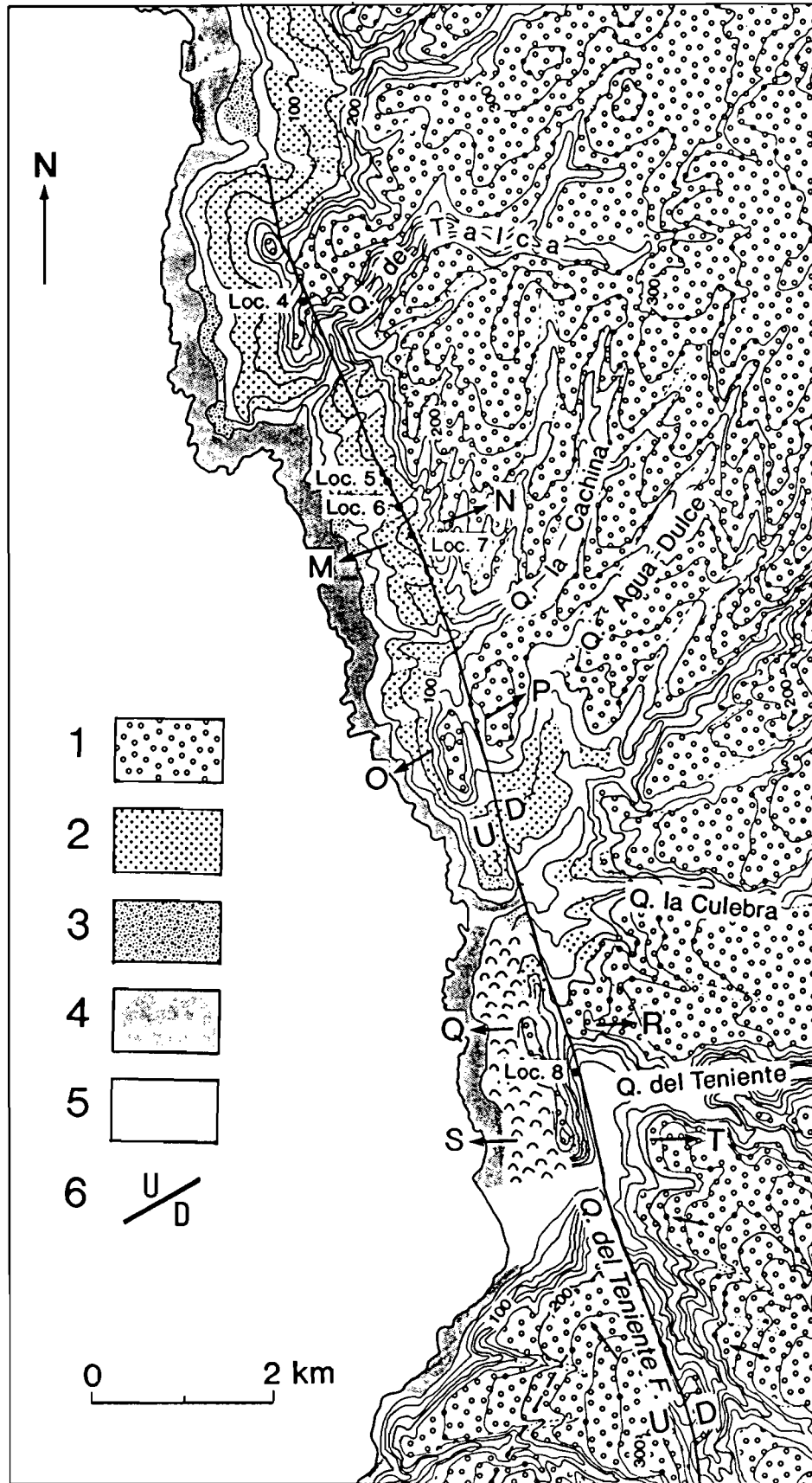


FIGURE 29. Geomorphological sketch of the Quebrada del Teniente area (Ota, Miyauchi, Paskoff and Koba, 1995).

1: Talinay I (Serena I ?) terrace. 2: Talinay II (Serena II ?) terrace. 3: Talinay III (Herradura I ?) terrace. 4: Talinay IV (Herradura II) terrace. 5: slope. 6: Quaternary fault.

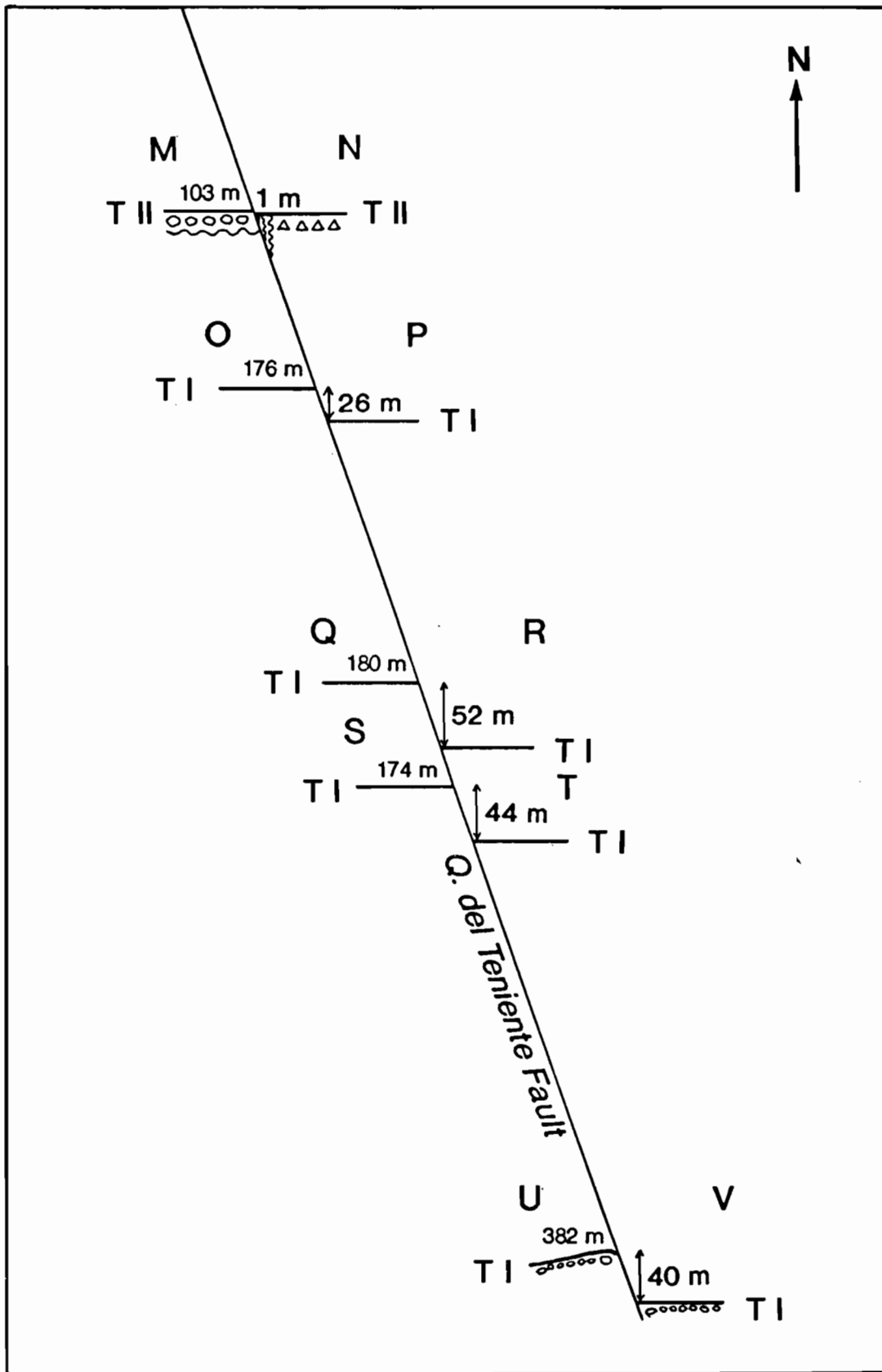


FIGURE 30. Diagram showing vertical displacement of marine terraces in various transects along the Quebrada del Teniente Fault (Ota, Miyauchi, Paskoff and Koba, 1995). Transect locations are shown in figure 29, except for Profile U-V which is shown in figure 26

apparent offset is actually caused by differential erosion between the soft upper Tertiary deposits on the downthrown side and the Paleozoic resistant metamorphic rock on the upthrown side. Recent geological mapping of the area confirmed this point of view (F. Hervé, written communication). North of Quebrada del Teniente, a rather thick dyke, which was dated 121,6 ky, crosses the Quebrada del Teniente Fault without any horizontal displacement.

The Quebrada del Teniente Fault is a normal fault with a east-facing scarp which is opposite in sense to the relief growth ("range-facing" scarp). No activity since the formation of the Talinay III (Herradura I ?) terrace was identified. So, the Quebrada del Teniente Fault is defined as a non active Quaternary fault. Generally speaking, it is important to note that there are no active faults in the Talinay Heights area (Ota, Miyauchi, Paskoff and Koba, 1995). Such a situation is very different from other subduction zones on the rim of the Pacific Ocean where there are many active faults which have been repeatedly active up to the present. This relative tectonic stability is probably related to a weakening of the coupling between the Nazca Plate and the South American Plate from the middle Quaternary onwards.

Southward, between Quebrada del Teniente and the Choapa River (fig. 31), over a distance of about half a degree of latitude, the Talinay I/Serena I platform, still affected by the east-facing Quebrada del Teniente Fault which runs parallel to the shoreline, continues as a typical *rasa*. However, it becomes lower as a result of a weakening of crustal movements in Plio-Quaternary times. From the mouth of the Choapa river (31°30' S) down to the mouth of the Aconcagua River (33° S), only moderately and evenly uplifted rocky wave-cut platforms are found (fig. 32). They resemble those described in the Coquimbo Bay area as far as their elevation is concerned. Therefore, the coastal belt of north-central Chile appears to be divided into independent segments, each one characterized by a different tectonic trend. Such a division probably reflects discontinuities and different behaviors in the underlying subduction zone (Paskoff, 1977).

From Coquimbo Bay (30° S) down to the mouth of the Aconcagua River (33° S), over three degrees of latitude, the lower marine terrace (Vega terrace) is remarkably constant. It starts at the present shoreline and extends to a height of 5/7 m at the foot of an abandoned cliff which can be observed everywhere along the coast at the same elevation, even in the strongly deformed Talinay Heights area. Surficial beach deposits capping this terrace are Holocene in age, as evidenced by radiocarbon datings (Paskoff, 1973; Ota and Paskoff, 1993). However, taking into account the slowness of marine erosion when hard rocks outcrop, it seems reasonable to assume that the lower terrace was actually cut by an interstadial transgression during the last glacial period (Cachagua episode of Herm and Paskoff (1967), stage 3 ?), being afterwards reoccupied

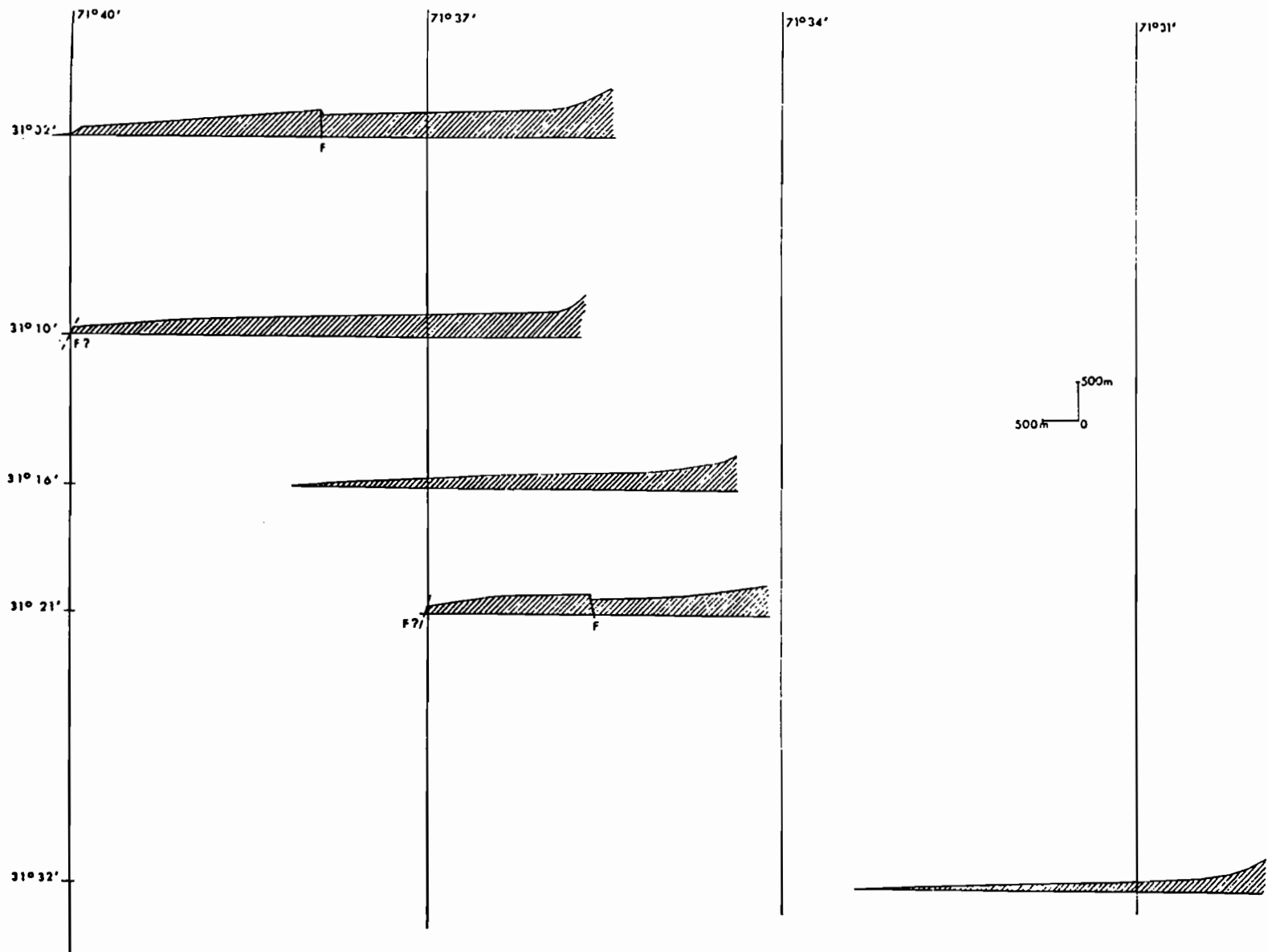


FIGURE 31. Topographic profiles across the wide wave-cut platform (Talinay I/Serena I terrace) between Quebrada del Teniente and the Choapa River (Paskoff, 1970).

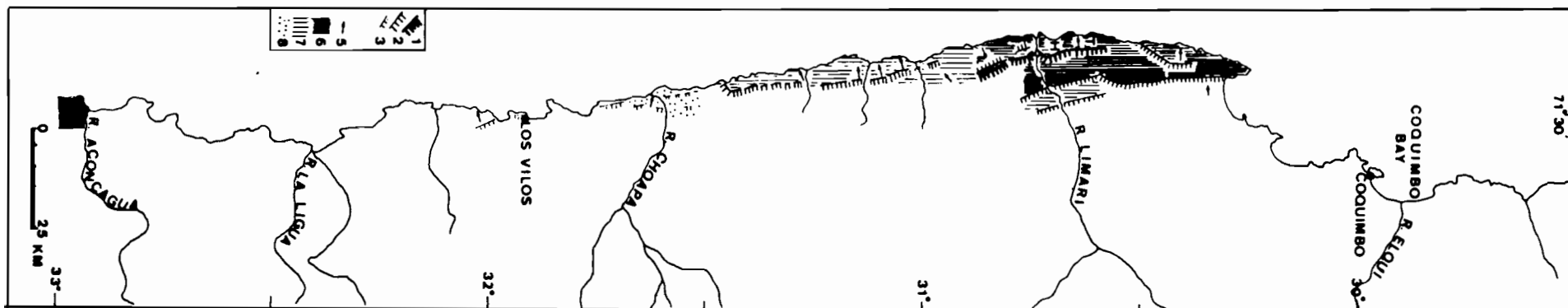


FIGURE 32. Plio-Quaternary crustal movements along the Chilean coast between latitude 30° and 33° S (modified from Paskoff, 1977).

- 1: fault scarp (throw more than 100 m). 2: fault scarp (throw between 10 and 100 m).
- 3: fault scarp (throw less than 10 m). 5: tilting. 6: strongly uplifted area. 7: uplifted area. 8: downwarped area.

and reworked by the Holocene transgression. Such example of terrace reoccupation was made possible because of the low uplift rate of the north-central Chile continental margin in recent Quaternary times. Discussion on this hypothesis by the attendants of the trip would be appreciated.

References cited

- Brüggen J. (1929). *Texto de geología*, El Globo, Santiago.
- Cooke R.U. (1964). Les niveaux marins des baies de La Serena et de l'Huasco dans le Nord du Chili, *Bulletin Association Géographes Français*, 320-321, 19-32.
- Darwin Ch. (1846). *Geological observations on South America*, Smith, Elder and Co, London.
- Domeyko I. (1848). Mémoire sur le terrain tertiaire et les lignes d'ancien niveau de l'Océan du sud, aux environs de Coquimbo (Chili), *Annales des Mines*, 14, 153-162.
- Furutani T. (1995). *Electron spin resonance (ESR) spectroscopic dating of fossil mollusks from uplifted marine terraces, west coast of the United States and Chile*, Unpublished Ph.D. dissertation, University of Washington.
- Herm D. (1969). Marines Pliozän und Pleistozän in Nord- und Mittel-Chile unter besonderer Berücksichtigung der Entwicklung der Mollusken-Faunen, *Zitteliana*, 2, &-159.
- Herm D. and Paskoff R. (1967). Vorschlag zur Gliederung des marinen Quartärs in Nord- und Mittel-Chile, *N. Jb. Min. Geol. Paläont. Mh.*, 10, 577-588.
- Hsu J.T. (1988). *Emerged Quaternary marine terraces in southern Peru: sea level changes and continental margin tectonics over the subducting Nazca Ridge*, Unpublished Ph.D. dissertation, Cornell University.
- Hsu J.T., Leonard E.M. and Wehmiller J.F. (1989). Aminostratigraphy of Peruvian and Chilean Quaternary marine terraces, *Quaternary Science Review*, 8, 255-262.
- Leonard E.M. and Wehmiller J.F. (1992). Low uplift rates and terrace reoccupation inferred from mollusk aminostratigraphy, Coquimbo Bay area, Chile, *Quaternary Research*, 38, 246-259.
- Leonard E.M., Muhs D.R., Ludwig K.R., and Wehmiller J.F. (1995). Coral Uranium-series ages and mollusc amino-acid ratios from uplifted marine terrace deposits, Morro de Copiapó, north-central Chile, *American Quaternary Association Program and Abstracts*, 13th Biennial Meeting, 223.
- Naranjo J.A. and Paskoff R. (1980). Evolución geomorfológica del desierto de Atacama entre los 26° y 33° latitud sur: revisión cronológica, *Revista Geológica de Chile*, 10, 85-89.

- Martínez R. (1979). Hallazgo de foraminíferos miocénicos cerca de Puerto Aldea, Bahía de Tongoy, provincia de Coquimbo, Chile. *Revista Geológica de Chile*, 8, 65-78.
- Möricke W. and Steinmann G. (1896). Die Tertiärbildungen des nördlichen Chile und ihre Fauna, *N. Jb. Min. Geol. Paläont.*, 10, 548-612.
- Muhs D.R., Kelsey H.M., Miller G.H., Kennedy G.L., Whelen J.F., and McInelly G.W. (1990). Age estimates and uplift rate for late Pleistocene marine terraces: southern Oregon portion of the Cascadia forearc, *Journal of Geophysical Research*, 95, 6685-6698.
- Novoa J.E. (1991). Cambios recientes en la línea litoral, área intercomunal La Serena-Coquimbo (IV Región), Chile semiárido, análisis comparativo (1954-1978), *Revista Geográfica de Chile Terra Australis*, 35, 35-45.
- Novoa J.E., Araya A.A., Fernández R.M. and Araya M.C. (in preparation). Análisis de riesgo por tsunamis, área intercomunal La Serena-Coquimbo.
- Orbigny (d') A. (1842). *Voyage dans l'Amérique méridionale*, 3, Paris.
- Ota Y. and Paskoff R. (1993). Holocene deposits on the coast of north-central Chile: radiocarbon ages and implications for coastal changes, *Revista Geológica de Chile*, 20, 25-32.
- Ota Y., Miyauchi T., Paskoff R. and Koba M. (1995). Plio-Quaternary marine terraces and their deformation along the Altos de Talinay, north-central Chile, *Revista Geológica de Chile*, 22.
- Paskoff R. (1968). Proposition de classification du Pliocène continental du Chili centre-nord, *C.R. somm. Soc. géol. France*, 7, 226-227.
- Paskoff R. (1970). *Le Chili semi-aride, recherches géomorphologiques*, Biscaye, Bordeaux
- Paskoff R. (1972). Morphogenèse quaternaire aux alentours de l'embouchure du río Elqui (province de Coquimbo, Chili). *Photo-Interprétation*, 4, 1-7.
- Paskoff R. (1973). Radiocarbon dating of marine shells taken from the north and central coast of Chile, *Abstracts IX INQUA International Congress*, New Zealand, 281-282.
- Paskoff R. (1977). The Quaternary of Chile: the state of research, *Quaternary Research*, 8, 2- 31.
- Paskoff R. (1991). Likely occurrence of a mega-tsunami in the middle Pleistocene, near Coquimbo, Chile, *Revista Geológica de Chile*, 18, 87-91.
- Paskoff R. (1993). *Geomorfología de Chile semiarido*. Universidad de La Serena.
- Radtke U. (1987a). Marine terraces in Chile (22°-32° S), geomorphology, chronostratigraphy and neotectonics: preliminary results II, *Quaternary of South America and Antarctic Peninsula*, 5, 239-256.
- Radtke U. (1987b). Palaeo sea levels and discrimination of the last and the penultimate interglacial fossiliferous deposits by absolute dating methods and geomorphological

- investigations illustrated from marine terraces in Chile, *Berliner geographische Studien* , 25, 313-342.
- Radtke U. (1989). Marine Terrassen und Korallenriffe. Das Problem der quartären Meeresspiegelschwankungen erläutert an Fallstudien aus Chile, Argentinien und Barbados, *Düsseldorfer Geographische Schriften*, 27, 1-246.
- Tsuchi R. (1992). Neogene events in Japan and on the Pacific coast of South America, *Revista Geológica de Chile*, 19, 67-73.
- Veit H. (1991). *Upper Quaternary soil landscape evolution in the lower Elqui valley between La Serena and Rivadavia (Chile, 30° S)*, Taller Internacional sobre Geoecología de los Andes, Manejo de Recursos y Desarrollo sustentable, Universidad de Chile y Universidad de las Naciones Unidas, Santiago, 16 p.
- Wehmiller J.F., Belknap D.F., Boutin B.S., Mirecki J.E., Rahaim S.D. and York L.L. (1988). A review of the aminostratigraphy of Quaternary mollusks from United States coastal plain sites, in Easterbrook D.L. (ed) *Dating Quaternary sediments*, Geological Society of America Special Paper, 227, 69-110.
- Willis B. (1929). *Earthquake conditions in Chile*, Carnegie Institution of Washigton, Publ. 382, 178 p.
- Zeuner F.E. (1959). *The Pleistocene period* , Hutchinson, Londres.

2978

1005
JUNES 88
ICCP Project 367
2nd annual meeting
ANTOFAGASTA, Chile
19-28 November 1988

ORION

