Quaternary Tectonic and Recent Seismic Crustal Movements in the Arauco Peninsula and its Environs, Central Chile

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ABSTRACT

An outer part of the outer arc in the arc-trench system is a zone where great earthquakes have occurred periodically and remarkable crustal movements have been recorded both at the great earthquake and at the inter-earthquake times. For comparing these short-term historical crustal movements with long-term Quaternary ones, the Arauco Peninsula in the Pacific coast of central Chile is one of the most suitable land on the earth to be studied. This is the reason why we investigated the Quaternary crustal movements in and near the Arauco Peninsula by means of geomorphology and Quaternary stratigraphy.

The Arauco Peninsula, which lies in the continental shelf zone bordering the Coastal Range of central Chile, consists of five gemorphic surfaces: Las Nochas, Buena Esperanza, Cañete, Lower terraces, and Holocene lowland surfaces in a descending order. The former three are marine terraces, and the latter two are partly marine and partly alluvial in origin. The topographic features and surface-making deposits of these surfaces show that each of the surfaces has been built during various periods of marine transgression, probably caused by an interglacial or an interstadial and a post-glacial uplift of sea level. Among these surfaces, the widest Cañete Surface, most probably formed in the last great interglacial or Sangamon Interglacial, shows composite features of two modes of crustal movements: a landward tilting and an upwarping with a NW-SE trending axis. NW-SE trending upwarping of the latter is also indicated by heights of elevated shorelines of the Buena Esperanza and Las Nochas Surfaces, and even by heights of erosional surfaces in the Nahuelbuta Mountains, a part of the Coast Range, lying east of the Arauco Peninsula. The erosional surfaces in the mountains, which were probably built in the late Tertiary, imply that a N-S trending upwarping has taken place during the Quaternary, superposing the above mentioned NW-SE trending one. Two islets, Santa María and Mocha in the continental shelf zone, off the northwestern and southwestern coasts of the Arauco Peninsula, consist of marine terraces. These marine terraces show a landward tilting during the late Quaternary. Radiocarbon datings for Holocene terrace deposits in Mocha Island indicate that the mean rate of uplift has been 55 cm per 100 years for the last several thousands years.

The mode of landward tilting during the late Quaternary in the shelf zone is just the same as that of co-earthquake crustal movements in the historical age, and the amount of late

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Quaternary tilting is most likely to have been formed by the accumulation of repeated co-earthquake tiltings; while the mode of the N-S trending Quaternary upwarping in the Nahuelbuta Mountains is rather reverse to that of co-earthquake movements, and thus the amount of the Quaternary upwarping of the mountains would have been formed by the accumulation of inter-earthquake movements. Based on this, the terms, *a zone of co-earthquake deformation* and *a zone of inter-earthquake deformation* are proposed to the shelf zone and the Coast Range respectively.

RESUMEN

La parte exterior del arco externo en el sistema arco-fosa es una zona donde han ocurrido los grandes terremotos períodicamente y se has registrado importantes movimentos de la corteza tanto en los terremotos mismos como en los períodos entre terremotos. La península de Arauco en Chile central es una de las regiones más adecuadas del mundo para comparar los movimientos de la corteza, sean históricos o cuaternarios. Este es el motivo porque hemos estudiado los movimientos cuaternarios de la corteza en la región de la Península de Arauco, con métodos geomorfológicos y estratigráficos.

La Península de Arauco se halla en la zona de la plataforma continental que linda con la Cordillera de la Costa, ye consiste en cinco superficies geomorfológicas por orden descendiente: Las Nochas, Buena Esperanza, Cañete, Las Terrazas Bajas y el aluvio del Holoceno. Estas últimas son marinas y aluviales en parte, mientras que las tres primeras son terrazas marinas. Según las características de topografía y sedimentación de cada superficie, consideramos que se han formado en un ambiente de transgresión marina quizás causada por levantamientos. interglaciales, interestadiales o postglaciales del nivel del mar. La superficie Cañete, la más extensa de las cinco, se ha formado seguramente en la última época interglacial (Sangamon). Esta superficie exhibe rasgos compuestos de dos modos de movimientos de la corteza: inclinación hacia el continente y combadura con eje NW-SE. Una combadura con la misma dirección se observa también en el desplazamiento de la costa de emersión de Buena Esperanza y Las Nochas, además en el desplazamiento de las superficies de erosión en la Cordillera Nahuelbuta, una parte de la Cordillera de la Costa ubicada al este de la Península de Arauco. La superficie de erosión de esta Cordillera, que se ha formado tal vez en el terciario superior, nos indica que ocurrió en el cuaternario la combadura con rumbo NW-SE y además otra con rumbo N-S. Las terrazas marinas que se hallan en dos islas, Santa María y Mocha en la plataforma continental al noroeste y suroeste de la Península de Arauco, fueron inclinadas hacia el continente durante el cuaternario superior. El levantamiento medio de la Isla Mocha ha sido de 55 cm por siglo según las edades C-14 de los depósitos de las terrazas.

La inclinación hacia el continente en la zona de la plataforma continental durante el cuaternario superior concuerda con los desplazamientos en los grandes terremotos históricos. La inclinación cuaternario en esta zona se puede explicar por el efecto acumulado de los terremotos. La combadura cuaternaria con eje N-S en la Cordillera de Nahuelbuta es opuesta al desplazamiento de los terremotos, por lo tanto se debió formar por el movimiento de la corteza entre terremotos. Por siguiente, proponemos aplicar los términos *zona de deformación co-sísmica* y *zona de deformación inter-sísmica* para la plataforma y la Cordillera de la Costa, respectivamente.

CONTENTS

I. INTRODUCTION

The arc-trench system is the most active region on the surface of the earth. Around the Pacific, there are many arc-trench systems, whole of which makes the circum-Pacific orogenic, seismic and volcanic belt.

Although arc-trench systems differ from one another in detail, every arc-trench system has a common feature in the macro-morphology, seismicity, crustal and subcrustal structures. In general, the system consists of three topographical units; an oceanic trench, a non-volcanic outer arc and a volcanic inner arc. The boundary between the non-volcanic outer arc and volcanic inner arc is the front of volcanic belt or volcanic front (Sugimura, 1960), which runs parallel with the trench at the distance of 100–300 km from the axis of the trench.

The outer arc is distinguished by its seismic activity; it is especially true near the trench where great earthquakes, together with associated regional crustal deformations, have been recorded. It has been noticed in the seaward parts of the outer arc of southwestern Japan that the mode of Pleistocene and Holocene crustal deformations has a characteristic in common feature, that is, an accumulation of landward tilting of the crust. This mode of deformation is similar to that of crustal displacements associated with great earthquakes occurred in the same regions (Sugimura and Naruse, 1954; Yoshikawa et al., 1964 a, b, 1968; Yonekura, 1968). Nearly the same mode of crustal displacements associated with great earthquakes has been reported from the Pacific coasts of Alaska and Chile, and the mode of displacement has been explained by an underthrust faulting between oceanic and continental lithospheres (Plafker, 1969; Plafker and Savage, 1970). The thrust-fault mechanism was also applied to explain the mode of crustal displacements associated with the 1923 and 1946 great earthquakes occurred in the Pacific coasts of southwestern Japan (Ando, 1971; Fitch and Scholz, 1971).

Thus it is becoming clear that the seaward part of the outer arc has a similar mode of deformation in the Quaternary and in the present; and also that the crustal deformation is caused by underthrust of the oceanic lithosphere beneath the outer arc at the trench.

Our knowledge of crustal deformation in the seaward part of the outer arc, however, is not enough to understand the whole features concerned, because: (1) the seaward part of the outer arc is under the sea, and (2) a systematic study of the Quaternary and present crustal deformations for the outer part of the outer arc started recently. Therefore, it is disired to be done more studies for the seaward part of the outer arc.

The Arauco Peninsula in central Chile is one of the most suitable region for that study on land, as well as the regions of the Mejillones Peninsula and the Tongoy area in northern coast of Chile. Because all these regions lie at the distance of 100 km from the Peru-Chile Trench axis. Moreover, the Arauco Peninsula has been attacked frequently, nearly once in every century, by great earthquakes; and the documents of crustal displacements associated with them are fairly abundant (Darwin, 1851; Plafker and Savage; 1970; Lomnitz, 1970). These are the reasons why we investigated this region under the financial support of the Japanese Ministry of Education.

Our first seismo-geological mission to Chile and Peru (Mision sismo-geología del Japón al Chile y Perú) spent about 40 days in the Arauco area from December 1970 to January 1971.

This is a primary report on the Arauco Peninsula and its environs. The main purpose of this article is to describe the topography and Quaternary geology, especially the evidence of crustal deformations during the Quaternary and the historical age in the region concerned. A discussion on the relationship between Quaternary crustal deformations and historical seismic dislocations will be added briefly.

The more general discussion on the neotectonics of the outer arc in the Andean Arc system will be stated in the near future, when the second seismo-geological mission in 1972 will finish the studies on crustal deformations in the Temuco-Valdivia region, southeast of the Arauco Peninsula.

II. REGIONAL SETTING

The Arauco Peninsula is located on the Pacific coast of central Chile between 37° and 38°S. The peninsula is a part of the Andean Arc and the Peru-Chile Trench system (Figs. 1 and 2).

1. The Andean Arc and the Peru-Chile Trench system

This giant arc-trench system has a typical arc-trench feature. A trench, a non-volcanic outer arc and a volcanic inner arc are arranged in this order from the oceanic side to the continent.

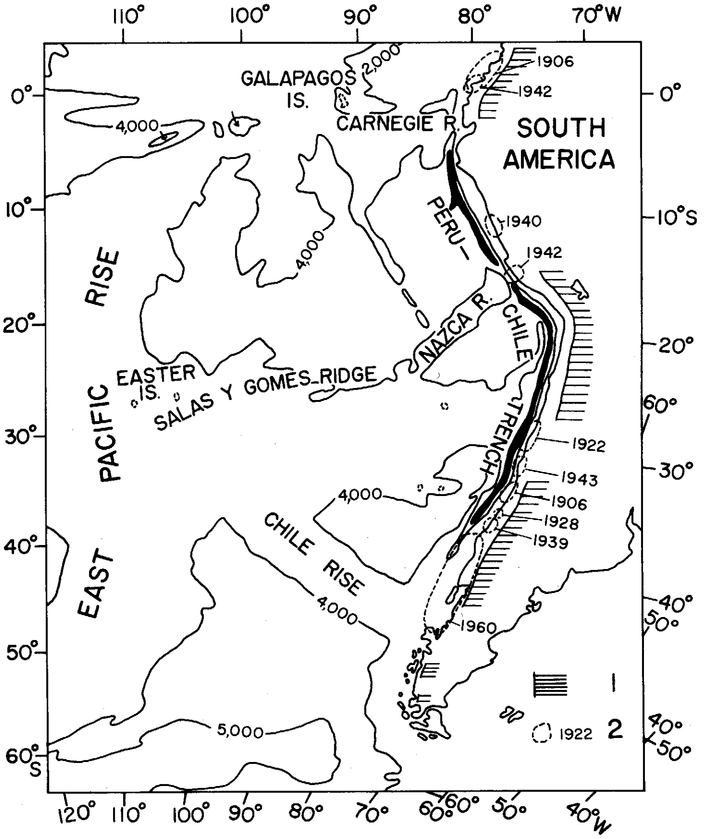

Fig. 1 Index map showing the Andean Arc-Trench system and the southeast Pacific.
1: Volcanic belt with volcanic front.
2: Region of great earthquake.

The Peru-Chile Trench extends from 4°N to 40°S, the deepest part of which reaching about 8000 m below sea level off the coast of Antofagasta at 23°S (Fisher and Raitt, 1962).

The non-volcanic outer arc is defined as the region between the inner wall of trench and the volcanic front. Generally, the outer arc is composed of a continental slope, a continental shelf, an outer arc rise and a mid-arc trough. In Chile, the outer arc rise is expressed as the Coast Range; the mid-arc trough, the Longitudinal (Central) Valley. While in Peru, both the outer arc rise and the mid-arc trough are generally expressed as a wide continental shelf. There are two exceptional areas; the northern coast of Peru and the landing place of the Nazca Ridge in southern Peru, where the outer arc rises are seen on land as coastal ranges.

Along the Chilean Pacific coast, the continental shelf is narrow. It is especially true off the coasts of the Mejillones and Arauco peninsulas, the distances from the trench axes to the coasts being 70 km and 100 km respectively. Such a short distance from the trench axis to the coast is rather unique in the world.

The Andean Mountains or the volcanic inner arc is 4000 to 6000 m high above sea level in its central part, decreasing its height to the south gradually until about 2000 m at around 40°S.

The outer arc is characterized by intense shallow seismic activities both of smaller earthquakes and of great ones (Fig 1). In the central and northern Andes intermediate and deep earthquakes occur, and the deepest hypocenters are as great as 650 km deep, whereas in the southern Andes, south of 29°S the deepest ones occur about 150–200 km (Santo, 1969), and south of 46°S no seismic activity is observed along the continental margin.

The thickness of the crust increases progressively from the Pacific basin floor to the Andes (Fisher and Raitt, 1962; Lomnitz, 1962), with an exception of the crustal thinning beneath the offshore flank of the trench (Hayes, 1966). The thickness reaches from about 10 km beneath the trench axis to 55–70 km beneath the Andes.

2. Physiographical and geological setting of the region studied

From south of Santiago to Puerto Montt (34°–42°S), there is a striking zonal arrangement of macro-morphology from the oceanic side landward — a trench, a continental slope, a continental shelf, the Coast Range, the Central Valley, and the Andean Mountains capped by volcanoes (Fig. 2). Generally, the width of the continental shelf is several tens kilometers, the Coast Range about 100 kilometers, and the Central Valley several tens kilometers.

The only one peninsula protruding to the Pacific along the coast south of Santiago is the Arauco Peninsula. Off the west coast of this peninsula, the width of the shelf is exceptionally narrow. According to the study of seismic reflection profiles (Sholl et al., 1970: Fig. 3), the continental shelf north of the Arauco Peninsula consists mainly of thick Tertiary strata, unconformably overlying upper Cretaceous rocks. The rocks of the Arauco Peninsula are also mainly composed of Tertiary strata overlying Cretaceous rocks. Hence the peninsula seems to be a raised part of the shelf zone.

The Tertiary strata in the Arauco Peninsula are of the Eocene, Miocene and Pliocene (Tavera, 1942; Muñoz Cristi, 1946, 1956; Brüggen, 1950; Zeil, 1964; García, 1968). The Eocene, consisting of marine and intercalated continental sediments with coal seams dips westward at about 20°, and is affected by block faulting. The strata of the marine lower and upper Miocene are named the Navidad and Ranquil Formation respectively. The Pliocene marine Tubul Formation is distributed in the northern part of the peninsula. The Pleistocene marine sediments, which will be described later in detail, truncate the above-mentioned "basement rocks", and are distributed over nearly the whole peninsula.

The Coast Range in the latitude of 34°–42°S is generally low-relief mountains as a whole lower than 1000 m above sea level. However, the Nahuelbuta Mountains (Cordillera de Nahuelbuta), which lies east of the Arauco Peninsula, attain an exceptional height of more than 1000 m, the highest point reaching 1530 m. No river traverses the mountains. On the northeast the mountains are bordered by the River Bío Bío, and on the south by the River Imperial, both of which start from the Andes and empty into the Pacific Ocean.

The Coast Range consists mainly of Precambrian or Paleozoic metamorphic rocks (Schist and phyllite) and granitic plutonic rocks. The Nahuelbuta Mountains also consist of these two kinds of rocks. Along the western slope of the Nahuelbuta, marine strata of the upper Cretaceous overlie the basement complex, striking N-S with a dip of 10° to 30° west as are

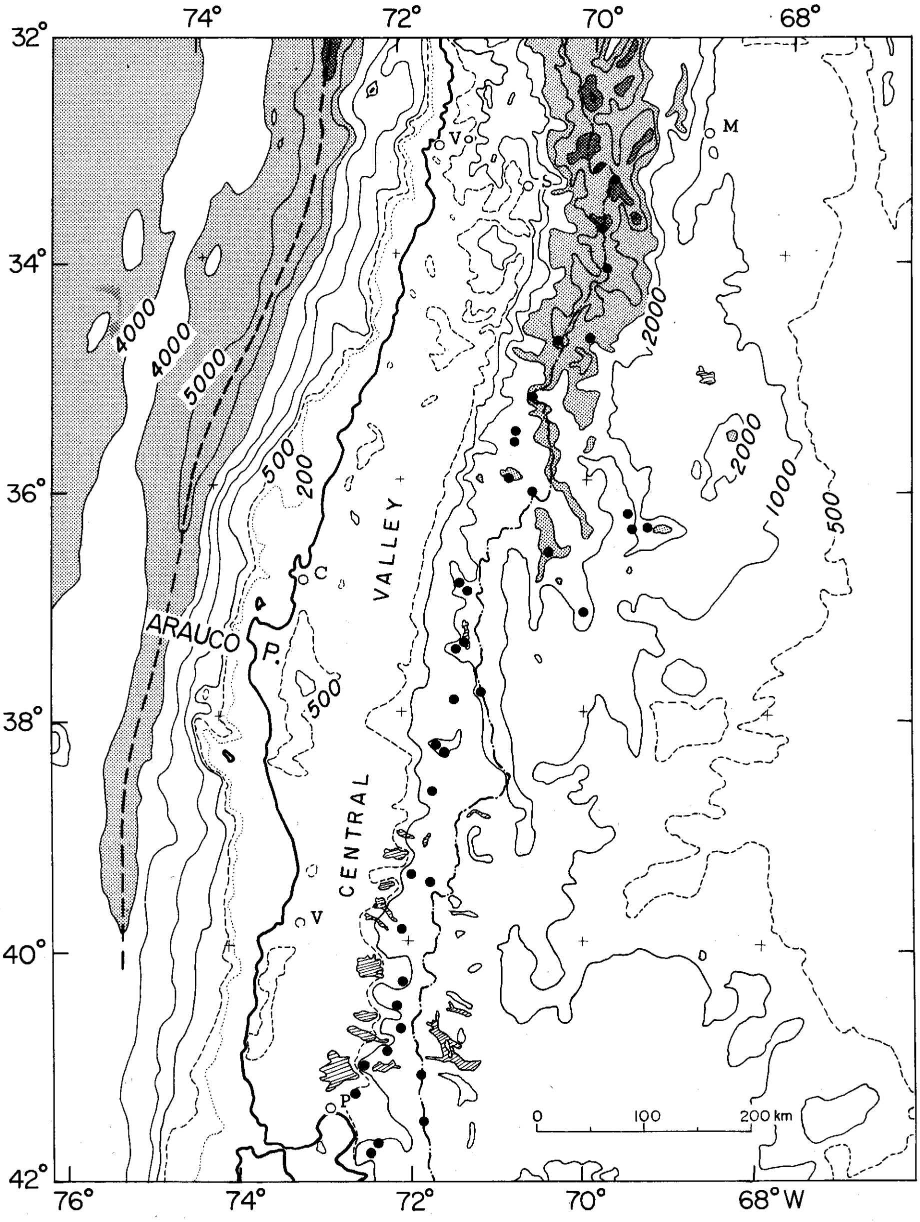

Fig. 2 Generalized topography of the Andean arc-trench system in central Chile.
Contour interval: 100m. Solid circle: volcano. C: Concepción. M: Mendosa. P: Puerto Montt. S: Santiago. Va: Valdivia. Vo: Valparaiso.

the Eocene strata in the Arauco Peninsula.

The present climate of the Arauco Peninsula is as follows. The annual precipitation is

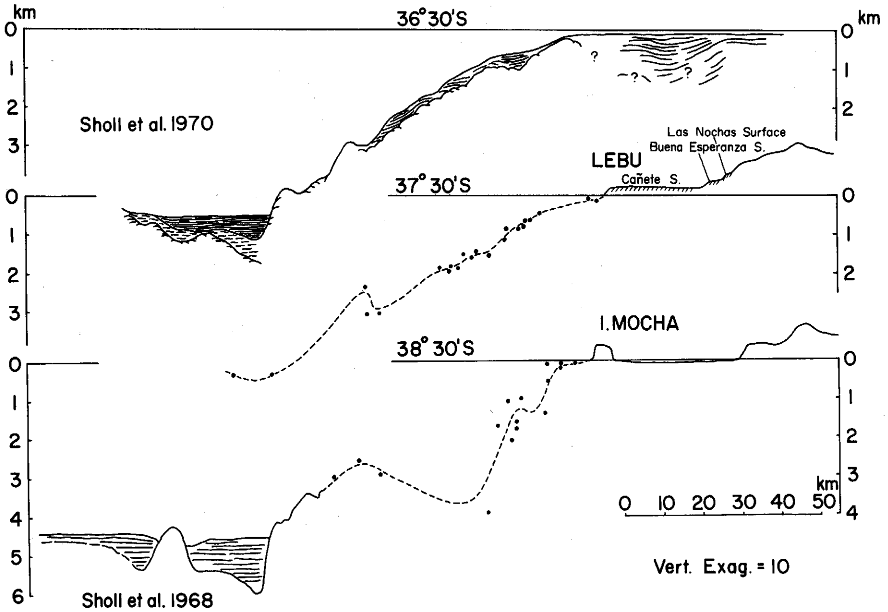

Fig. 3 Cross sections from the trench to the coastal area in and near the Arauco Peninsula.
Submarine sections are drawn from Sholl et al., 1968, 1970 and from a chart, No. 3075 published by Hydrographer of the Navy, U.K.

about 1500 mm (mainly in winter). The mean temperature is around 8–9°C in winter, 16–17°C in summer, and the annual mean is about 13°C.

III. GEOMORPHOLOGY, QUATERNARY GEOLOGY AND QUATERNARY CRUSTAL MOVEMENTS IN THE ARAUCO PENINSULA AND ITS ENVIRONS

1. Previous studies

It has been known that the Tertiary formations in the Arauco Peninsula are covered unconformably with marine Pleistocene deposits. The deposits were named the Arauco Formation by Muñoz Cristi (1968), and subdivided into older and younger ones by Stiefel (1968). The studies of the Pleistocene deposits, however, have scarecely been done so far.

A terrace surface widely distributed in the peninsula was called as"meseta pliocenica" (Pliocene table-land) by Brüggen (1950). According to Stiefel (1968), the terrace surface is partly an erosional surface cutting the underlying Tertiary formations, and partly a depositional one of the Pleistocene deposits. This terrace surface is designated as middle terrace surface (or Cañete Surface) in this paper.

It has been described by Brüggen (1950) and Stiefel (1968) that the terrace surface is the highest in the east of Los Alamos, from where the altitude of the surface descends both to the north and south. This feature of the surface, which must be ascribed to crustal deformation, is concerned with a main subject of this paper.

Brüggen (1950) also pointed out that between this terrace and the Nahuelbuta Mountains there exists a higher marine terrace with thin deposits, and that the highest part of the terrace lies to the east of Los Alamos. This terrace is designated as higher terraces in this paper and their deformations are also an important subject of this paper.

As to the topography of the Nahuelbuta Mountains, it has been noted that there are remnants of peneplanated surfaces, and their altitudes imply an upheaval of the mountains in the Pleistocene (Brüggen, 1950; Muñoz Cristi, 1956).

2. The Nahuelbuta Mountains

Fig. 4 is a Gipfelflur showing topographic features of the Nahuelbuta Mountains and the Arauco Peninsula. A projected profile of the mountains is shown in Fig. 13. The Gipfelflur contour lines are drawn based on the highest points in 2x2 km quadrangles on 1: 50,000 topographic maps. The projected profile is drawn based on the highest points in east-west belts of 2 km in width.

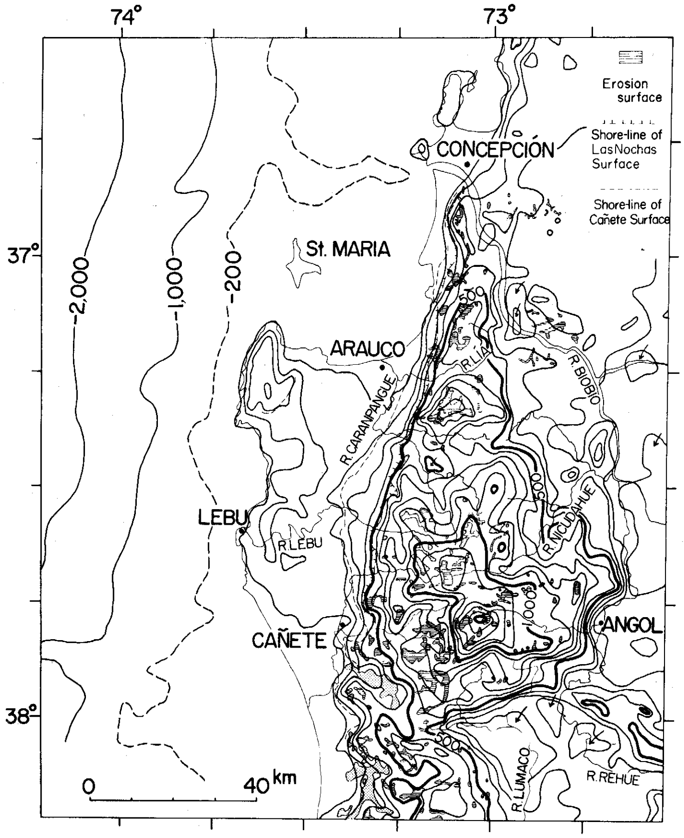

Fig. 4 Gipfelflur of the Nahuelbuta Mountains and the Arauco Peninsula.
Contour interval: 100 m

As shown in these figures and Photo 1, the altitudes of the mountains decrease from the highest peak of 1530 m gradually to the north and abruptly to the south. On the west, the mountains are bordered by fairly steep slope running straight nearly north-south. While on the east, the bordering slope is rather gentle and runs irregularly. The width of the mountains is larger in the south than in the north.

Referring to the 1000 m contour line, it is noted that the central high of the mountains extends in the NW-SE direction. Interesting is that the mountains in the northwestern part of the Arauco Peninsula lie just on the northwestern extension of this high, and also as seen in the later part of this paper (Fig. 12), an axis of uplift of the Cañete Surface lies nearly along this extension.

As shown in Fig. 4, low-relief erosion surfaces are distributed with various heights in almost whole area of the Nahuelbuta. The distribution is drawn based on our interpretation from aerial photographs (about 1:40,000 in scale) and topographic maps (1:50,000).

The origin of these erosion surfaces seems to be due not to marine abrasion, but to subaerial denudation. In the field, we examined the erosion surfaces at several places: northeast of Coronel, northeast of Carampangue and southeast of Curanilahue. But we could not find any marine deposits overlying the basement rocks.

Judging from the altitudes of the erosion surfaces, it can be said that most of them were made once as a peneplain under the same base-level of erosion. The age of the peneplanation is not evident, but it must be younger than the Eocene strata, and older than the Pleistocene marine terraces. Probably the age falls in the late Tertiary. Thus the present altitudes of the erosion surfaces seem to indicate an areal variation of crustal deformation since the late Tertiary.

The Nahuelbuta Mountains are dissected by steep valleys of the youth stage of erosion. This fact as well as the deformation of terraces in the eastern part of the Arauco Peninsula implies that the deformation and upheaval of the mountains took place mainly during the Quaternary, as stated by Brüggen (1950) and Muñoz Cristi (1968).

3. Pleistocene terraces and Holocene lowland in the Arauco Peninsula

The landform of the Arauco Peninsula is composed of marine terraces, which are subdivided into higher, middle and lower terraces, and Holocene lowland. These divisions are shown in the geomorphological map (Fig. 5) based on airphoto interpretations and field observations.

Altitudes of raised shorelines of the marine terraces were read on altimeters in the field or on topographical maps, and are shown by numerals in Fig. 5. Altimeters of the American Paulin System Terra MT-2 were used and correction for barometric changes was made by using a Barograph of the same System.

A. Higher terraces

The higher terraces are distributed along the western foot of the Nahuelbuta (Photos 1 and 2), and in the northwestern mountains of the Arauco Peninsula which were called as "cerros de Yane-Lavapie" by Brüggen (1950).

The higher terraces along the western foot of the Nahuelbuta are composed of two terrace surfaces, the upper of which is designated here as the Las Nochas Surface, and the lower as the Buena Esperanza Surface. Both surfaces are fairly dissected by valleys, but original terrace surfaces are partly preserved.

Las Nochas Surface

The deformed shoreline of the Las Nochas Surface reaches up to 500 m in altitude at

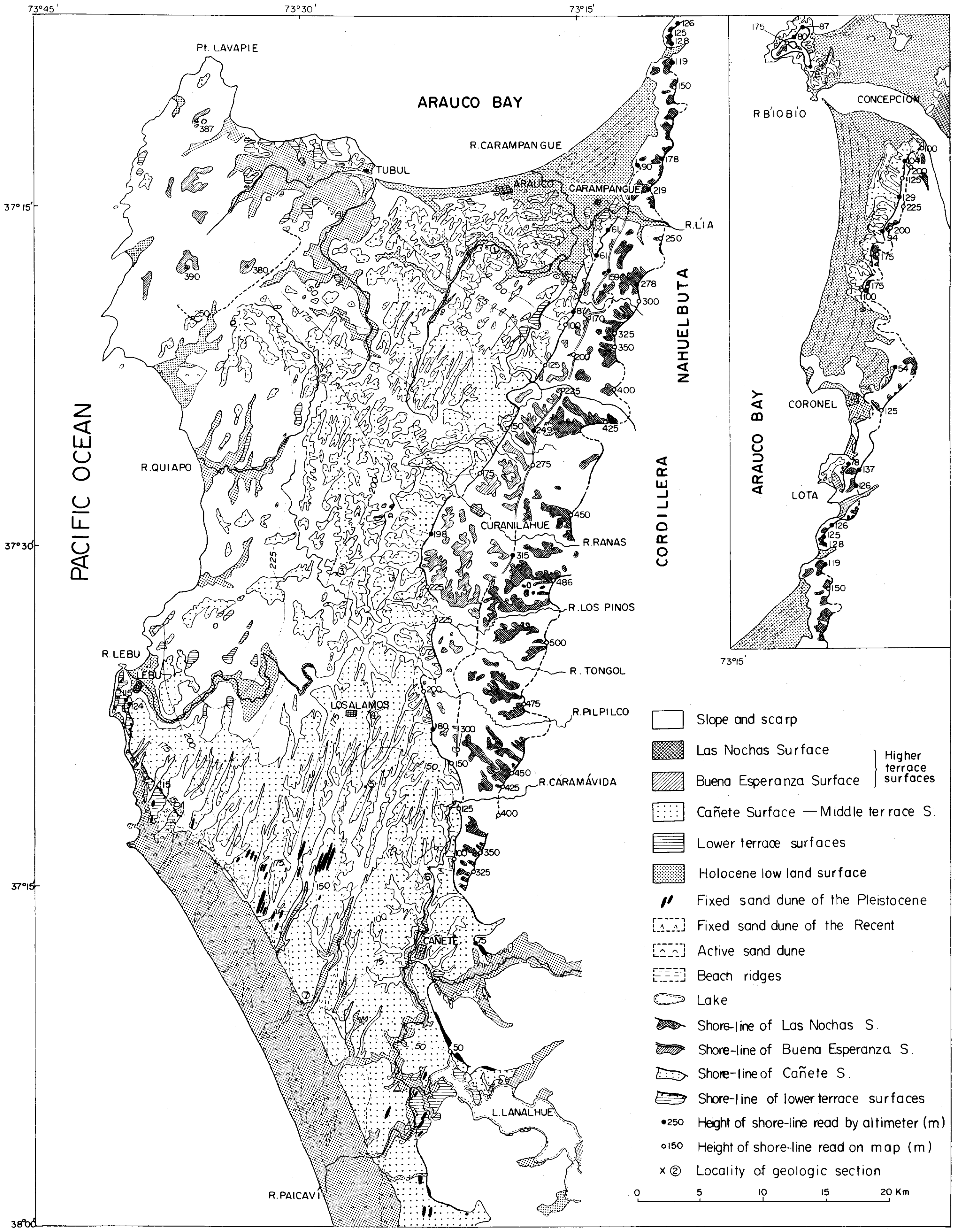

Fig. 5 Geomorphological map of the Arauco Peninsula.

37°35′S, from where altitudes of the shoreline decline both to the north and to the south. The width of the surface is in a few kilometers and is widest around the highest shoreline.

The terrace surface is, broadly speaking, an abrasion platform cutting the basement complex of metamorphic and Eocene rocks. The terrace deposits are generally thin, and composed of sand, pebbles and partly boulders. In places, however, thick marine terrace deposits are found; for example, at Descabezado, 5 km southeast of Curanilahue, sand and gravel beds of more than 20 m thick are present.

The terrace deposits have been weathered to such an extent that they are reddish brown to reddish orange in color (7.5R 5/6 – 10R 6/8 in Munsell Color Chart).

The elevated shoreline of the Las Nochas Surface is not straight, but indented as shown in Fig. 5. This feature of the shoreline indicates that there were many small embayments curved in the Nahuelbuta Mountains when the marine terrace was built.

Considering such an irregular shoreline feature and the existance of thick terrace deposits, it is obvious that the terrace was built under an environment of ria coast, in other words, under the environment of marine transgression.

Buena Esperanza Surface

This surface extends along the western foot of the Nahuelbuta Mountains between Las Nochas and Cañete Surfaces. The highest shoreline is about 340 m high above sea level at the south of Curanilahue, where the terrace surface reaches the greatest width. The shoreline angle of this terrace is not so obvious as that of the Las Nochas Surface. To the north of Lota, the shoreline and terrace surface are not preserved.

This terrace surface is mainly an abrasion platform, which truncates the basement of schist, Cretaceous and Eocene strata. In places, however, we saw marine beds consisting of sand, silt and pebbles, for instance at 3.5 km southeast of Curanilahue. The Buena Esperanza shoreline is less indented than that of the Las Nochas Surface.

Higher terrace on the northwestern mountains in the Arauco Peninsula

The northwestern mountains, being less than 400 m high, consist of Eocene strata. Valleys in the mountains are prevailingly in the NE-SW direction. They may have been built under a structural control of the Eocene rocks, since the strata strike to the same NE-SW direction.

On summits of the mountains there present flat or low-relief surfaces of 325–390 m in height. Although no research works have been done as to the surface-making deposits, judging from their topographic features they must have been built as a marine terrace originally.

Altitudes of the surface are kept nearly constant in the N-S direction from the northern end, near Punta Lavapie at 37°12′S to the south at 37°19′S, and they also vary little in the E-W direction. Hence it may be concluded that significant differential vertical displacements have not been taken place in this mountains since the surface was built.

We tentatively correlate this higher terrace surface with the Buena Esperanza Surface in age based on their altitudes.

B. Middle terrace (Cañete terrace)

Topography of the Cañete terrace and its drainage system

The middle terrace occupies most of the area of the Arauco Peninsula. The terrace surface is widely preserved except in the western part of the peninsula where it has mostly been lost by fluvial erosion (Fig. 5). This surface is designated as the Cañete Surface after the name of the largest town located on the surface.

As shown in Figs. 5 and 12, the altitude of the surface is highest (225–250m) in the western part of the peninsula, from where it declines northeastward and southeastward until it comes to less than 100 m. The former shoreline angle of this terrace is well preserved along the western border of the Nahuelbuta from near Concepción (36°45′S) to Cañete (37°50′S). Near Cañete the raised shoreline enters valleys in the Nahuelbuta and makes an irregular feature. Therefore, the shoreline must have been formed along a ria coast.

The highest altitude of the shoreline along the western border of the Nahuelbuta is 225 m above sea level at the northeast of Los Alamos, from there decreasing to the north and south (Figs. 5 and 12). Around the northwestern mountains of the peninsula, the shoreline angle of the Cañete terrace is not well preserved, although the mountains must have been an island surrounded by the sea shore at the time of the Cañete Surface. The altitude of the raised shoreline is 225–250 m above sea level in the southern part of the mountains.

Rivers which dissect the Cañete Surface in the northeastern and southeastern parts of the peninsula flow consequently to he surface features that are shown by the restored contour lines in Figs. 5 and 12, while in other parts of the peninsula rivers run inconsequently to the surface features. For example, the largest river in the peninsula, the River Lebu (Rio Lebu), flows to the west cutting through the highest part of the Cañete Surface (Photo 5). It is most likely that the River Lebu is an antecedent river.

Of interest to mention is the fact that valleys running NNE-SSW are dominant in the southern and also, to some extent, in the northern parts of the Cañete Surface. This peculiar drainage system seems to be developed under topographic control of longitudinal dunes of the NNE-SSW direction, which will be described in the succeeding section.

Middle terrace deposits: the Cañete Formation and superficial deposits overlying it

The Pleistocene deposits forming the middle terrace are designated as the Cañete Formation. The main part of the formation is marine, and the uppermost part is eolian in origin. In some places fluvial deposits are found above the Cañete Formation, but eolian loamy deposits are common in most places above it. A geological map of the Cañete Formation is shown in Fig. 6 and columnar sections in Fig. 7.

Distribution, thickness and sequence of the Cañete Formation. As shown in Fig. 6, the thickness of the formation is large in the northeast and southeast parts of the terrace reaching 60 m, while small in the central part less 20 m, and especially small or almost lacking in the central east and northwest parts, where the Eocene strata and Precambrian schist are exposed as the basement rocks. The terrace surfaces in these central east and northwest parts are located near the ancient shorelines, thus the surfaces are inferred as abrasion platforms in origin. Since the detail basal topography of the Cañete Formation is not clear, the thickness variation shown with contour lines in Fig. 6 indicates the general tendency.

The Cañete Formation can be divided into the lower marine beds consisting mostly of thick sand and the upper eolian beds of thin sand. The boundary between them is not necessarily sharp.

Marine beds of the Cañete Formation. The marine beds consist mainly of sand, but in some horizons especially in the lower, of pebbles, cobbles and boulders. Silt layers are also

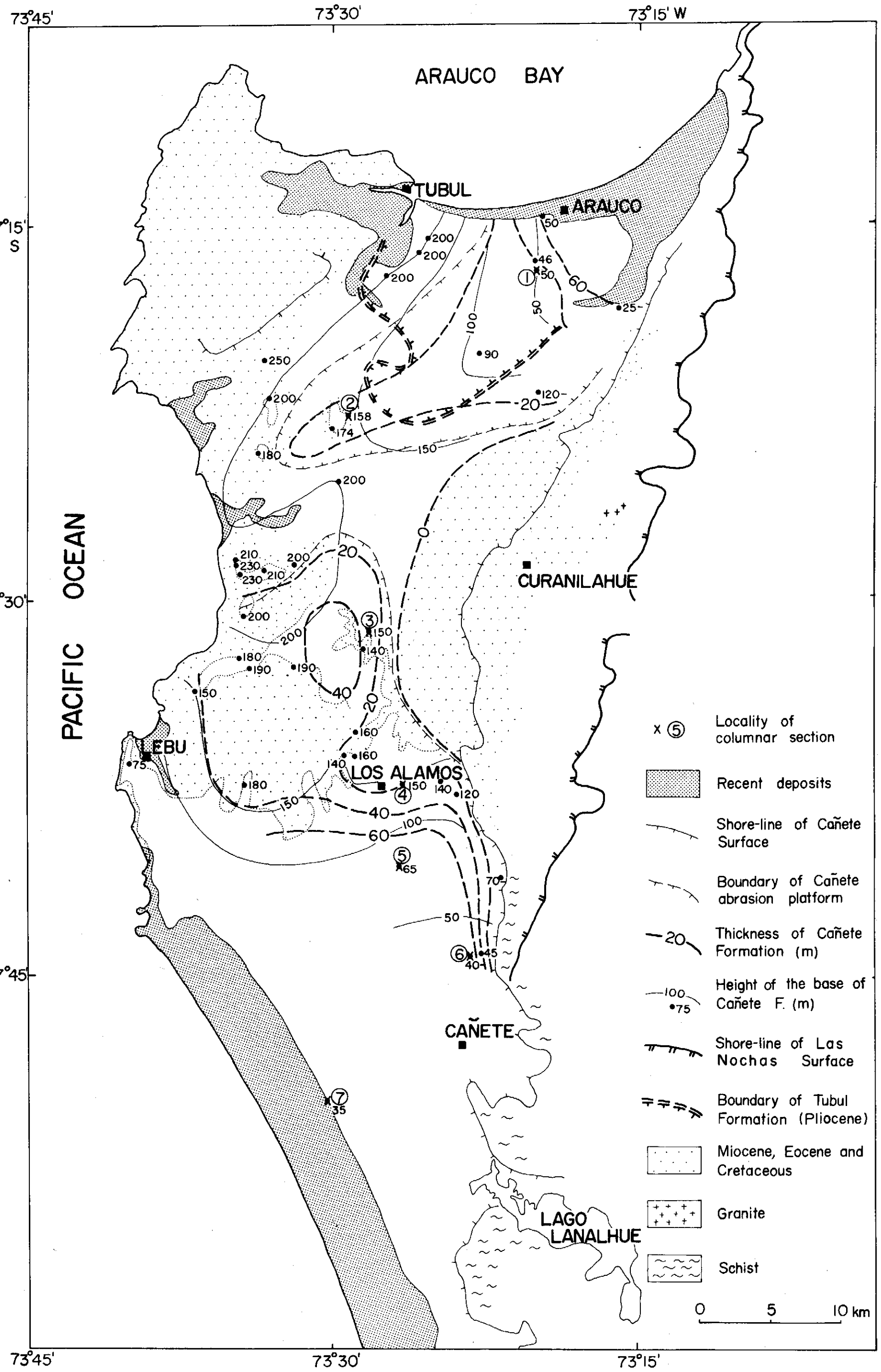

Fig. 6 Geological map of the Arauco Peninsula showing geology of the Cañete Formation.

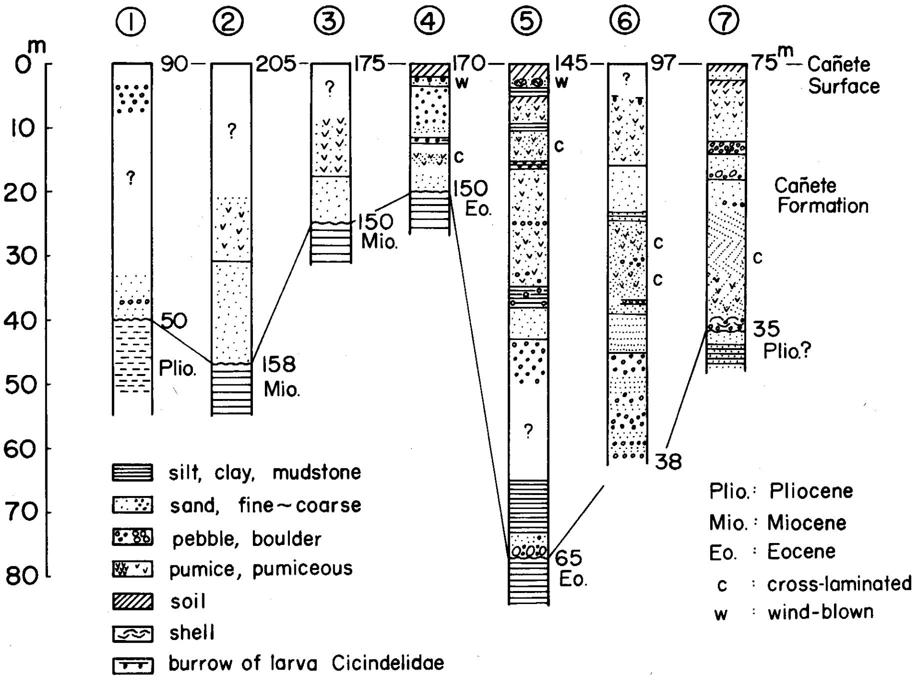

Fig. 7 Columnar sections of the Cañete Formation. Localities are shown in Fig. 5 and 6. Numbers represent height above sea level in meters.

intercaleted in some places (Fig. 7), and marine molluscan fossils are seen at the basal parts of the formation (Column 7 in Fig. 7).

Gravels are round or subround in shape. Sand is generally well-sorted. In the middle part sand layers show cross lamination in general. Some sand beds contain many grains of mica and some others do many grains of quartz, whose origin is probably schist and granites in the Nahuelbuta. It is noted that sand beds in the upper and middle horizons contain a lot of pumice grains. The source of the pumice grains may be primarily due to the Andean volcanoes southeast of this region. These pumice grains might be originated as pumice flows and then transported by fluvial processes along ancestral courses of the present River Imperial or Toltén from the Andes to the coast and further transported north to the Arauco Peninsula by longshore currents.

This interpretation depends on the following facts that the rocks of the Nahuelbuta could not be sources of pumice grains and that the prevailing wind and longshore current in this region would have been from south to north in the Pleistocene as well as in the present. Thus the origin must be anywhere to the south of the peninsula. The secondary source area is reasonably considered as the coastal area between the Imperial and Toltén rivers to which pumiceous volcanic material would easily be supplied from the volcanoes of the Andes.

Eolian bed of the Cañete Formation. The uppermost part of the Cañete Formation consists of widely-distributed eolian sand beds. These beds are composed of well-sorted fine to medium sand including whitish small pumice grains. The sand beds are firmly consolidated, hence they can be said eolianite (Photo 3). The thickness of the beds are 1–3 m in general, but where the sand beds make dune topography (see Photo 1) the thickness reaches more than several meters. Sometimes the sand beds are separated into two or three horizons by buried soil layers.

The sand dunes made of these sand beds extend widely in the southern part of the Cañete Surface. Some of them having distinct dune form are shown in Fig. 5 under the nomination of "fixed sand dune of the Pleistocene". Generally they are longitudinal dunes with NNE-SSW elongation. To the east and southeast of Cañete town, sand dunes of the same horizon mask the south-facing ancient shoreline angles of the Cañete Surface, so that the altitudes of shoreline were unable to be measured there.

The eolian beds are generally overlain by a bright brown to reddish brown loamy soil of 1–3 m thick (Photo 3), which will be mentioned later. Beneath this soil and just in the uppermost part of the eolianite, there are seen fossil burrows in many places. Most of them are found in the eolian beds as described below, but some are found in boulders of eolianite or not-eolian sand beds on the abrasion platform of the Cañete Formation.

Fossil burrows in eolian sand as an indicator of sedimentary environment. The burrows are ordinarily dug from the surface of eolianite perpendicularly as deep as about 10 cm with a diameter of 1–3 cm (Photo 3). They are found not only in the eolianite of the upper Cañete Formation, but also on the surface of dune sand overlying the lower terrace surface, and even in recent dune sand on the lowland.

Fortunetly, we could find a dried remain of an insect from a burrow in recent dune sand on the lowland of southeastern coast of the peninsula. This insect is identified as a larva of tiger beetle (*Cicindelidae*) by zoologist Yuzo Kitazawa and entomologist Kazuyoshi Kurosa. They suggest that the fossil burrow features in the eolianite bed of the Cañete Formation were made by the same kind of larva as what we found, and that the environment, wherein some kinds of tiger beetle larva like to live, is consistent with the environment that we estimated from the eolianite, that is, a barren sand field.

From this line of evidence, it is apparent that the Cañete Surface was once widely masked by wind-blown sand when the surface had emerged from the sea. The direction of sand-carrying wind was most probably south or southwest as indicated by the axial directions of elongated sand dunes.

Superfical deposits overlying the Canēte Formation. On rare occasions there present thin beds 2–5 m thick, consisting of gravels, sand and silt, which overlie uncomformably the Cañete Formation (Photo 4). These beds seem to be fluvial deposits of streams, which flew temporarily on the Cañete Surface when the surface emerged from the sea. These beds are also mantled with loamy soil (Photo 4).

The loamy soil, which mantles the whole surface of the Cañete Formation and the superficial fluvial deposits, is silty loam of 1–3 m in thickness and is bright brown to reddish brown in color. This loamy deposit is a kind of air-laid materials, perhaps loess and/or volcanic ash in origin, judging from its mode of deposition and grain size. The same kind of loamy deposit masks the lower terrace surface too, though the thickness is less than that on the middle terrace surface.

Tertiary formations underlying the Cañete Formation

Tertiary formations in the Arauco Peninsula are, as stated already, composed of the Pliocene, Miocene and Eocene sediments. The Pliocene Tubul Formation, which is distributed in the northern half of the peninsula (Fig. 6), consists of grey massive siltstone including marine fossil shells in some places. Foraminifera yielded in it has been studied by Martínez (1968 a).

The Miocene and Eocene formations are exposed in the eastern part and central (Curanilahue-Lebu) area of the peninsula. These formations dip to the west in general. The Miocene in the central area is mainly of massive mudstone scarcely including fossil shells. The Eocene formation occurring the eastern part consists mainly of sandstone beds with coal seams. The sandstone beds have been weathered to yellow to brown in color generally. Sometimes it is difficult to distinguish the weathered Eocene rocks from the Cañete Formation.

Physiographic development of the middle terrace

The Cañete Formation is a sedimentary unit formed during a marine transgression. Before the transgression, there was a dissected land in the area of the present Arauco Peninsula on the western foot of the Nahuelbuta. As the marine transgression progressed, the land submerged to form ria coasts in this region along the western border of the Nahuelbuta Mountains.

During the maximum stage of the transgression sequence, a wide abrasion platform was built and a depositional surface of the Cañete Formation as well. The duration years of stillstand of sea level at the maximum stage can be roughly estimated from the width of the abrasion platform, based upon our experience on postglacial abrasion platforms in Japan, as 10,000 years or so.

During the following regression stage, the Cañete Surface emerged above the sea level as a newly born coastal lowland, which was successively covered by sand and sand dunes under southerly wind. The eolian sand was accumulated much more in the southern coast than in the northern coast of the Arauco Peninsula. Such a difference between the northern and southern coasts in the Pleistocene time is consistent with the difference in the present state of sand accumulation between the both coasts (see Fig. 5).

On the way of landing of the Cañete Surface, many rivers extended from the surrounding mountains on to the Cañete Surface, and also many newly born streams having their catchment areas in the Cañete Surface appeared. These rivers and streams cut down the surface. The large extended rivers took their course consequently to the general submarine topography of the Cañete Surface, while small stream courses were determined by the small relief on the Cañete Surface such as the NNE-SSW longitudinal dunes.

Physiographic development of the Cañete Surface is much affected by the deformation of this region, which will be mentioned in later sections.

C. Lower terraces

Lower terraces are both marine and fluvial in origin. Marine lower terraces are distributed locally along the coast of the peninsula, and fluvial terraces along rivers in the peninsula (Fig. 5). Relatively wide lower terraces are described in the followings.

Along the River Caramphangue, northeast of the peninsula

Near La Meseta, east of Carampangue town, there are low table-lands which are 16–17 m high above sea level. These terraces consist of fluvial sand and silt.

The 16 m high lower terrace at Ramadillas, 6 km southwest of Carampangue town, is composed of fluvial sand and subangular gravels.

Along the River Tubul, northern coast of the peninsula

Around the alluvial lowland of the River Tubul, there are at least three levels of terrace surfaces, 20–30 m, 50–60 m, and about 80 m high above sea level, but we have no knowledge about their terrace deposits.

Near Lebu, western coast of the peninsula

There are several small steps of terraces just near the town of Lebu, as follows. The highest terrace (a) has the shoreline at about 150 m in height, the second (b) at about 125 m, the third (c) at about 115 m, the fourth (d) at about 100 m; and further lower fragmental terraces (e) exist. The terraces (a), (b), (c), and (d) are inferred as marine terraces, and each surface seems to be an abrasion platform. At the (c) terrace we observed deposits of 3–5 m thick pumiceous sand and gravels.

Along the River Lebu there are fluvial terraces, 150–200 m high above sea level.

Around 10 km south of Lebu, there is a marine lower terrace having a 116 m-high shoreline. This may be correlated to the (b) or (c) terrace near Lebu. The surface of this terrace is masked with eolianite. From this terrace to the south no marine lower terraces can be seen, notwithstanding there present a high continuous sea cliff between the middle terrace and lowland (Fig. 5 and Photo 6). This can be explained in such a way that near Lebu the basal rocks of the Eocene is hard enough to protect the lower terraces from marine erosion, but to the south basal rocks consist mainly of the unconsolidated Cañete Formation instead of the Eocene, so lower terraces was eroded completely to form the high sea cliff behind it by marine erosion.

Along the River Paicaví, southeast of the peninsula

Along the River Paicaví, south of Cañete town, occur fluvial terraces of 25–30 m in height, the surfaces of which are several meters lower than the Cañete Surface. On these terraces dune sand (eolianite) is distributed.

As stated in the preceeding paragraphs, there are many levels belonging to the lower terraces in separate localities, but it is difficult to correlate with each other. It is also difficult to mention whether marine transgression occurred or not during the age of the lower terraces. However, it is convincing that magnitude of the marine transgression, even if it occurred, was much smaller than that of marine transgressions at the time of the Las Nochas, Cañete and Holocene lowland surfaces, the last one of which will be described in the succeeding section.

D. Holocene lowland

Holocene coastal lowlands are distributed along the coasts, and Holocene alluvial lowlands along the downstreams of large rivers (see Photo 5).

The topographic features of alluvial lowlands in the downstreams suggest that there were drowned valleys before the deposition of alluvial sedimets. This view has been supported by bore-hole data in the lowland of the mouth of the River Lebu (García, 1968), which show that there lie 60–70 m thick "Quaternary" deposits upon the basal rocks. A similar view was so far expressed by Martínez (1968 b), who studied the Holocene deposits near Concepción. He concluded that the Holocene or Frandrian transgression occurred there.

As is shown in Fig. 5, the coastal lowland along Arauco Bay is characterized by many lines of beach ridges, while the lowland along the southern coast of the peninsula, by sand fields and a large number of sand dunes. Some of these sand dunes are fixed by plants, and others are barren and active at the present, as represented in Fig. 5 and Photo 6.

4. Marine terraces of Santa María Island

Santa María Island (Isla Santa María) lies north of the northwestern cape (Punta Lavapie) of the Arauco Peninsula. This island is 12 km in north-south length and consists of marine terraces and a lowland morphologically. The altitude of this island is less than 80 m above sea level (Fig. 8). On this island we spent two days, studying the marine terraces.

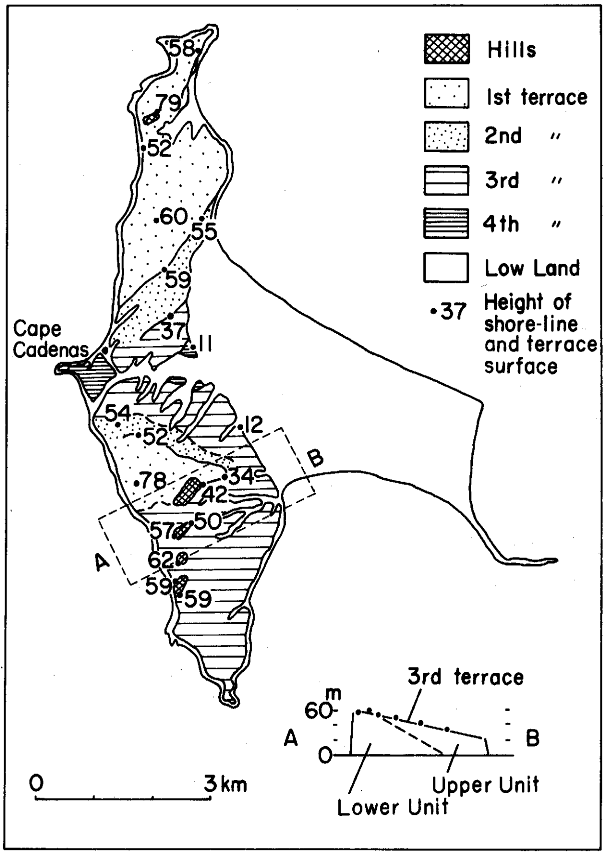

Fig. 8 Geomorphological map of Santa Maria Island.

General geology

As far as our observation is concerned, the main part of the island is composed of two sedimentary units: the lower one consists of massive mudstone and the upper, of stratified tuffaceous sandstone and siltstone. According to the geological map prepared by Muños Cristi (1946), the lower unit is Eocene in age, but after R. Martínez (oral comunication) it belongs to Miocene-Pliocene in age. The upper unit may be correlated with the Cañete Formation.

A conspicuous unconformity between the upper and the lower units are exposed widely on sea cliffs of the west coast and partially on sea cliffs of the east coast. Along the western sea cliffs, the boundary is situated 20–40 m high above sea level in the northern part, below sea level around Cape Cadenas in the central part, and up to the top of the 60 m high sea cliff at 2 km south of Cape Cadenas in the southern part. Along the eastern sea cliffs, altitudes of the boundary are lower than 5 m above sea level. Hence, east-west cross section of the island, as is shown in the lower section of Fig. 8, suggests a general tendency of eastward dip of the unconformity.

Marine terraces

This island consists of a series of terraces and a fairly wide lowland which occurs in the eastern half of the island. The terraces can be divided into four levels, termed the First, Second, Third, and Fourth terraces in descending order (Fig. 8). Above the First terrace surface there exist scattered small hills (Photo 7). Judging from their topographical features, most terraces seem to be marine in origin though our observation of terrace deposits was extremely limited. The highest First terrace surface is likely to be a depositional surface of the upper sedimentary unit, and the scattered hills are most probably composed of the lower unit.

In Fig. 8 altitudes of shorelines are indicated by numerals at our measured locations as well as altitudes of some flat terrace surfaces after topographic maps. In the field we noticed that each terrace surface inclines to the east-northeast (see Photo 7). The same trend of inclination is also found from the distribution of altitudes of each shoreline. This tendency is obviously seen at projected altitudes of the Third terrace shoreline as shown in the lower section of Fig. 8. The altitudes of this shoreline range from 60 m to 34 m in height above sea level in a distance of 2 km, so the degree of tilting since the age of the Third terrace is about 1° (1.3 per cent).

Although we have no reliable information regarding ages of the terraces, the First terrace is possibly correlative with the Cañete Surface in the Arauco Peninsula according to their altitudes and morphology.

5. Marine terraces of Mocha Island

Mocha Island, a spindle-shaped island of 13 km in length (Fig. 9), lies near the outer edge of the continental shelf southwest off the Arauco Peninsula. The axis of the Chile Trench lies about 90 km off the island. Morphologically the island is composed of two units: mountains capped by higher and middle terrace surfaces, and a lower terrace surface surrounding the mountains (Fig. 10 and Photo 9). We investigated the lower terrace for two days on the island.

General geology

According to Tavera and Veyl (1958), this island consists of marine Tertiary rocks, of which the Miocene Navidad and Ranquil Formations strike NE-SW to NW-SE with westward dip of 5–40°. These Miocene formations occupy the main part of the island. The Pliocene formation is also exposed along the southeastern coast of the island dipping gently westward.

Higher and Middle terraces

The Higher and Middle terraces of 200–400 m in height are distinctly separated from the Lower terrace lower than 33 m by a steep ancient sea cliff, which was formed contemporaneously with the Lower terrace (Photo 9). The Higher terrace of 330–390 m in

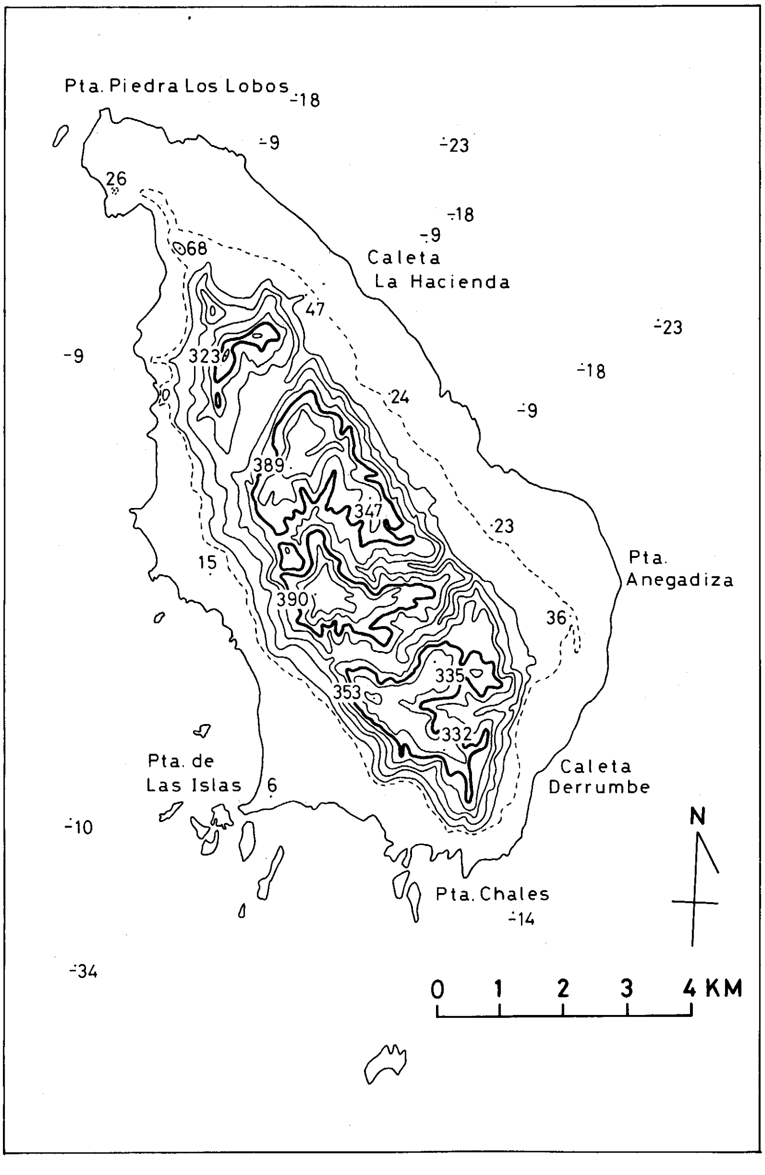

Fig. 9 Topographical map of Mocha Island. Contour interval: 50 m.

height is fairly dissected, and is partly underlain by unconsolidated 5 m thick deposits consisting of round gravels and fine sand (Tavera and Veyl, 1958). The deposits and the geomorphological features indicate that the Higher terrace is a marine terrace. This terrace surface tilts eastward at a gradient of 2–4 per cent. Most rivers dissecting the mountains run eastward consequently to the inclination of the surface.

The Middle terrace is distributed separately on the mountains. An altitude of the shoreline angle is about 250 m above sea level at the southern part of the island.

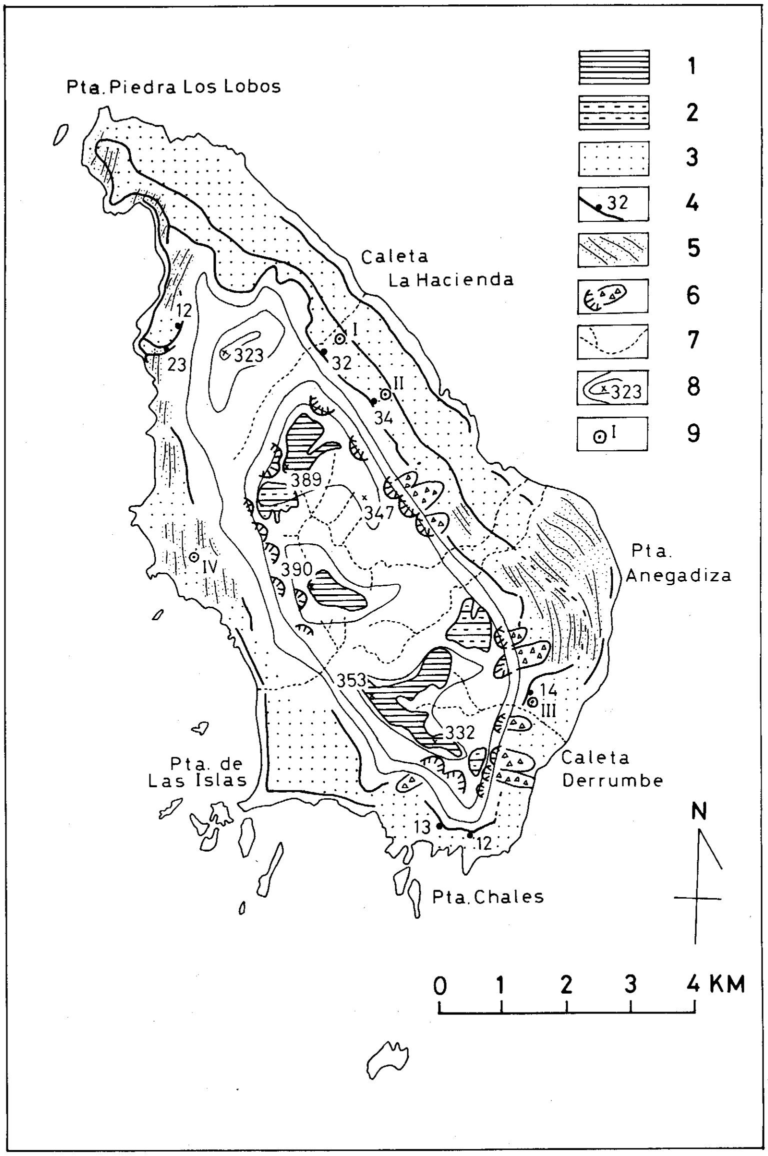

Fig. 10 Geomorphologial map of Mocha Island.
1: Higher terrace. 2: Middle terrace. 3: Lower terrace.
4: Shoreline of the Lower terrace and its altitude (in meters above sea level). 5: Sand dune and dune crest. 6: Rockfall scarp and rockfall deposits. 7: Stream. 8: Generalized contour line (interval: 100m) and altitude (in meters above sea level). 9: Sampling locality for radiocarbon dating.

There is no strict evidence for the ages of the Higher and Middle terraces, but it is likely that the higher one may be correlated to the Cañete Surface in the Arauco Peninsula.

Lower terrace and its absolute age

The Lower terrace fringes the island entirely along the coast. This terrace is subdivided into several sublevels by small cliffs, whose bases are raised shorelines. The highest sublevel develops on the east coast, and the highest raised shoreline reaches 33 m above sea level, near Caleta La Hacienda (Fig. 10). Many elevated beach ridges are observed along the northeastern coast (Photo 9). These raised shorelines and beach ridges indicate that the island has been uplifted repeatedly.

The Lower terrace as a whole is a rocky wave-cut platform underlain by thin beach deposits of gravels, sand and shell fragments (Photo 10), and partly covered by sand dunes. As shown in Fig. 10, the large elevated sea cliff has a number of rockfall scarps, some of which appeared at the time of the 1960 great earthquake. These rockfall deposits also cover the Lower terrace surface at the foot of the sea cliff.

Radiocarbon dating for beach deposits (fossil shell fragments, Photo 10) from four localities on the Lower terrace (Fig. 10) was carried on at the Laboratory of Dating, Gakushuin University, Tokyo, and the results obtained are shown in Table 1.

Table 1. Radiocarbon dates of shell fragments on the Lower terrace in Mocha Island.

Location (shown in Fig. 10)	Altitude (m above sea level)	Carbon-14 age (years B.P.)	Code no.
I	25	3920±90	GaK–3709
II	20	3930±100	GaK–3710
III	14	2590±110	GaK–3708
IV	10	1990±80	GaK–3711

The calculation is based on the Libby's half life of C-14, 5570 years. The sample of present shells was dated as "modern", δC-14=+1.75±1.0% (GaK–3712)

As is indicated in Fig. 11, the radiocarbon ages suggest that 1) the average rate of uplift is about 55 cm/100 years since 4000 years ago, and 2) the age of the highest shoreline of the Lower terrace (33 m high above sea level) is about 6000 years ago if the average rate of uplift is extraporated. Thus the obtained age of 6000 years is compatible with the well-known stage of 6000 years ago, when the world-wide sea level rised up to nearly the present sea level.

Therefore, it can be concluded that the general feature of the Lower terrace had been formed by marine abrasion up to 6000 years before under the rising sea level, and that since then Mocha Island has been uplifted intermittently with average rate of 55 cm/100 years under nearly a stable sea level.

6. Change of sea level and ages of the marine terraces

From the foregoing description about the landforms of marine terraces and the height of elevated shorelines, it is clear that the Arauco Peninsula and its surroundings have been displaced by vertical crustal movements during the late Quaternary. Mocha Island, above all, shows remarkable rate of uplift as revealed by the high altitude of the Holocene terrace.

Of interest to mention is a fact that Mocha Island has an evidence of the Frandrian transgression recorded by the dated Holocene terrace and the high sea cliff behind it, although the island has been uplifted strongly. This means that the rate of eustatic sea level

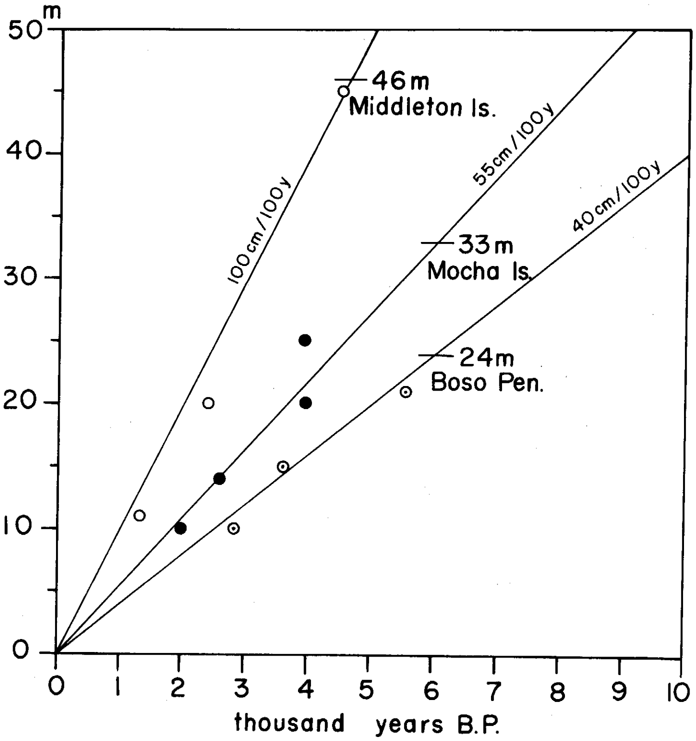

Fig. 11 Rate of upheaval in the Holocene in Mocha Island, Chile, Middleton Island, Alaska and the Boso Peninsula, Japan. Original data for Middleton Island are in Plafker and Rubin (1967), for Mocha Island are in this paper, and for the Boso Peninsula are unpublished data of N. Yonekura.

rise is higher than the rate of land uplift. Numerically, the former is known as about 1 m/100 years for 16,000 to 6,000 years ago, and the latter is 0.55 m/100 years.

Generally speaking, in an uplifting land, such a superiority of the rising rate of sea level over the uplifting rate of land is necessary for coastal terrace building. Therefore, when we find a marine terrace in uplifting lands, especially when we find thick marine terrace deposits and/or raised ria coast features, it is safely concluded that the terrace was built under a circumstance of rising sea level, in other words, according to the theory of glacial eustasy, under world-wide interglacial or interstadial circumstances

This line of thinking, which was born so far at the time of coastal terrace study in Shikoku, southwestern Japan by Yoshikawa, Kaizuka and Ota (1964.a, b, 1968), may be applicable to the Pleistocene terraces of the Las Nochas, Buena Esperanza and Cañete terraces as well as the Holocene terrace surface in Mocha Island. Hence these Pleistocene surfaces seem to have been formed in world-wide interglacials or interstadials. The Cañete Surface, the youngest and widest one among them may be of the last great interglacial or the Sangamon interglacial age, about 100,000 years ago. This estimation has not so much discrepancy with an estimated age of 60,000–80,000 years ago for the Higher terrace of Mocha Island, which seems to be correlated to the Cañete Surface as mentioned already. The age estimation of the Higher terrace in Mocha Island is based on the assumption that the mean rate of uplift obtained from the Lower terrace, 55 cm/100 years, was responsible for elevating the Higher terrace to the present altitudes, 330–390 m above sea level.

Accordingly the Buena Esperanza Surface and the Las Nochas Surface should have been formed in some of interglacials or interstadials preceding the last great interglacial, and the lower terraces of the Arauco Peninsula have been formed in some minor interglacials preceding the last glacial or some interstadials in the last glacial age.

7. Summary of Pleistocene and Holocene vertical crustal movements

It is concluded from our results that the dominant mode of crustal movements in the Arauco Peninsula and its surroundings is up - and down-warping or tilting. Any active fault, which cut the Quaternary terrace surfaces, is not recognized by us, although the presence of a fault or faults have been presumed (e.g., Saint Amand, 1961).

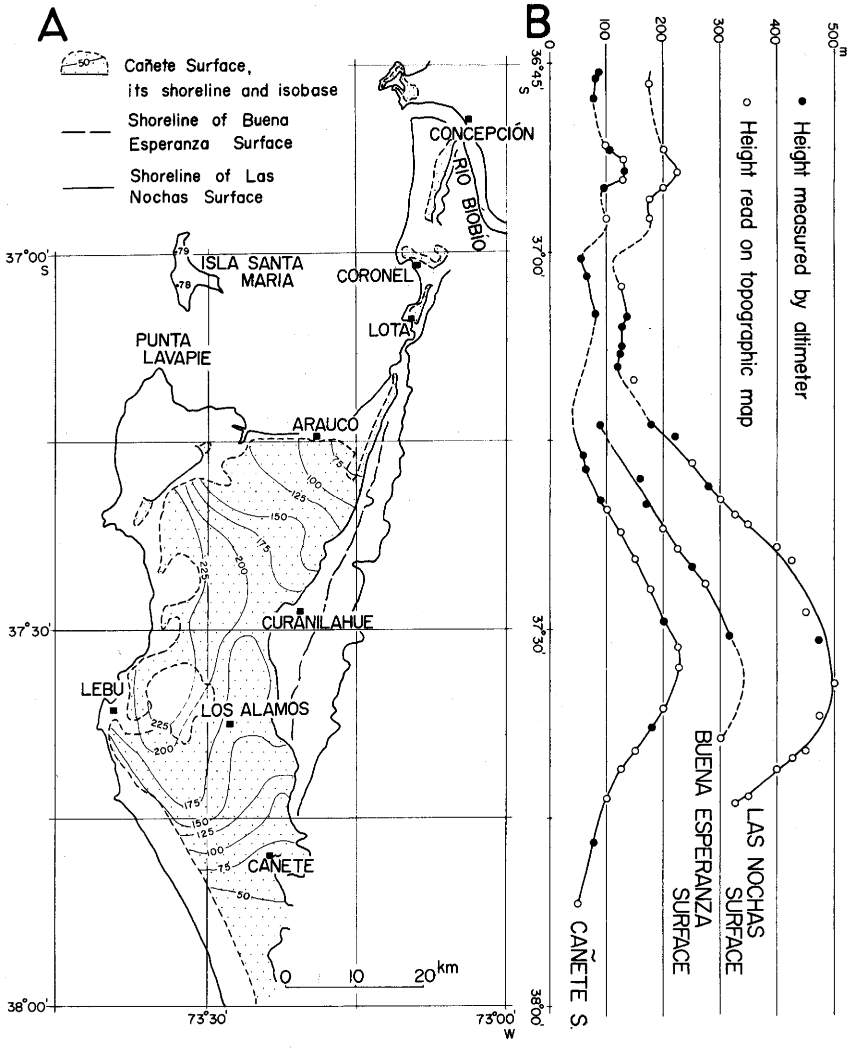

Fig. 12 Isobase or restored contour lines of the Cañete Surface (A) and longitudinal projection of shoreline heights (B).

In the left half of Fig. 12, isobase contours of the Cañete Surface are shown. Strictly speaking, the isobase contours do not represent an exact mode of crustal movements, but represent restored contour lines of the Cañete Surface. Roughly speaking, however the restored contour lines are regarded as lines of equal uplift, since the initial form of the Cañete Surface, which was a cut-and-built submarine platform, might have been as small as less than 20 meters in relief.

In the right half of Fig. 12, longitudinal projected profiles of the higher and middle terrace shorelines are shown. From this figure it can be said that the mode of tectonic deformation of the peninsula is just like as a saddle of horse. In other words the mode is composed of two series of warping, one nearly N-S, the other nearly NW-SE in trend.

As for N-S trending warping, axes of uplift are situated along the western coast of the peninsula and in the Nahuelbuta, and an axis of subsidence is nearly in the central part of the peninsula. This subsiding axis seems to extend north to Arauco Bay, and south to the shelf area between Mocha Island and the continent. The eastward tilting of Santa Maria and Mocha Islands also indicates that the uplift axis is situated on the outer rim of the continental shelf zone, and the subsiding axis on the coast side.

As for the NW-SE trending warping, an axis of uplift is given by the line that connects the highest parts of the higher and the middle terrace shorelines. The southeastward and northwestward extensions of this line pass the highest part of the Nahuelbuta, and nearly the northwestern mountains of the peninsula respectively, as is previously noted.

It is worthy of note that the mode of shoreline deformations of the higher and middle terraces bordering the Nahuelbuta is closely related to the heights of the Nahuelbuta

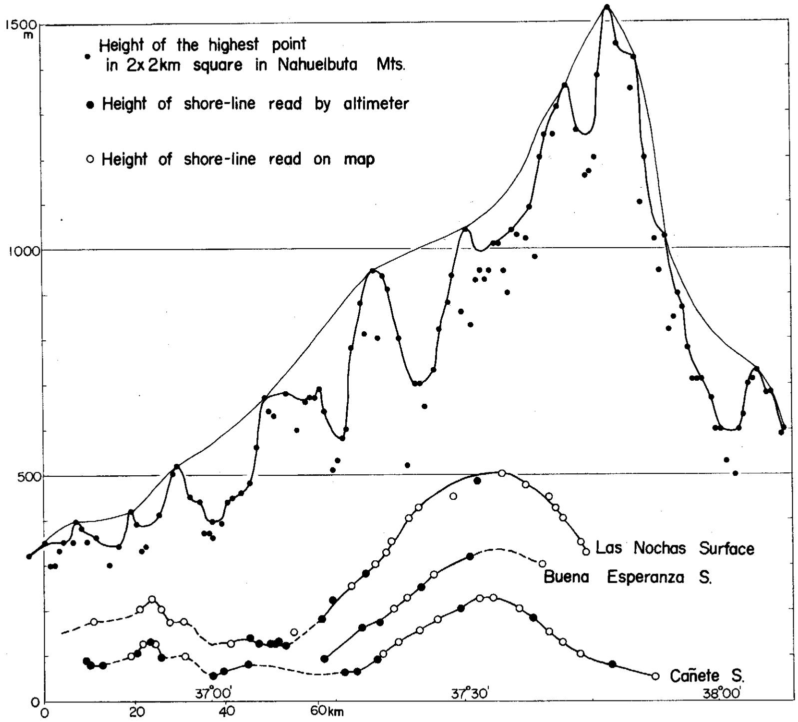

Fig. 13 Projected profile of the Nahuelbuta Mountains and heights of shorelines to longitudinal plane.

Mountains, as shown in Fig. 13. The longitudinally projected crest line of the mountains seems to be an amplified shape of the deformed shorelines of the higher and middle terraces Accordingly, it is concluded that the NW-SE trending warping is dated back far older than the time when those shorelines were formed. Probably they have continued since the erosion surfaces had been formed in the Nahuelbuta.

The NW-SE trending axis of uplift must have created the Arauco Peninsula as an exceptional protrusion along the Chilean coast. If there had been no NW-SE uplift in this area, the land of the peninsula should have been a part of the submarine continental shelf zone.

The above-mentioned saddle-shaped deformation in the Arauco Peninsula is consistent with the distribution of the Plicane Tubul Formation, which is seen only in the downwarped of the northern peninsula (Fig. 6). Thus, the saddle-shaped deformation may have continued since the Pliocene Epoch. This mode of deformation, however, is inconsistent with the structure of the Miocene and Eocene formations, which dip westward in general in the peninsula. Therefore it is expected that the change of tectonic mode happened in the Pliocene Epoch. The change of tectonic mode is also found in Mocha Island, where the Miocene strata dip westward while the Pleistocene terraces dip eastward.

IV. RELATIONSHIP BETWEEN RECENT DEFORMATIONS ASSOCIATED WITH GREAT EARTHQUAKES AND QUATERNARY CRUSTAL DEFORMATIONS

1. Tectonic deformations associated with the 1960 Chilean great earthquake

The 1960 great earthquake sequence started on May 21, 1960 with an intensive foreshock, whose epicenter was located in the Arauco Peninsula. The main shock (Richter magnitude of about 8.5) occurred on May 22, 1960. Its epicenter was located in the continental slope off Mocha Island (Fig. 14). The main shock was followed by after shock series. The aftershock area was very long along the continental margin, from 36.5°S to 48°S, and mainly between the trench and the volcanic front in east-west extension (Saint Amand, 1961).

The 1960 great earthquake was, according to Plafker and Savage (1970), accompanied by up - and down-warping along the continental margin between 37°S and 46°S, and from the trench to the volcanic front. The extent of the deformation coincided with the aftershock area. The regional vertical displacement was characterized by a broad asymmetric warping elongated parallel to the trench without any significant faults on land. A marked uplift occurred in the continental shelf zone and probably much or all of the continental slope as indicated by tsunami generation. The vertical upward displacement at the tsunami source area is estimated at 5.7 to 10 m on an average from the tsunami energy (Hatori, 1966). The maximum observed uplift on land was 5.7 m on Guamblin Island (43.5°S) located close to the outer edge of the continental shelf. On the other hand, a remarkable subsidence occurred in the Coast Range. The maximum measured subsidence was 2.7 m near Valdivia. Relatively minor uplift less than 1 m was observed along the western margin of the Andes Mountains This asymmetric warping is divisible into two sectors in profile by an axis of the maximum subsidence which lies nearly along the crest of the Coast Range. To the west of the axis, it is characterized by a steep continentward tilting, whereas to the east it shows a gentle seaward tilting. The width of a steep continentward tilting zone, namely the distance from the inner wall of the trench to the axis of the maximum subsidence, is about 150 km.

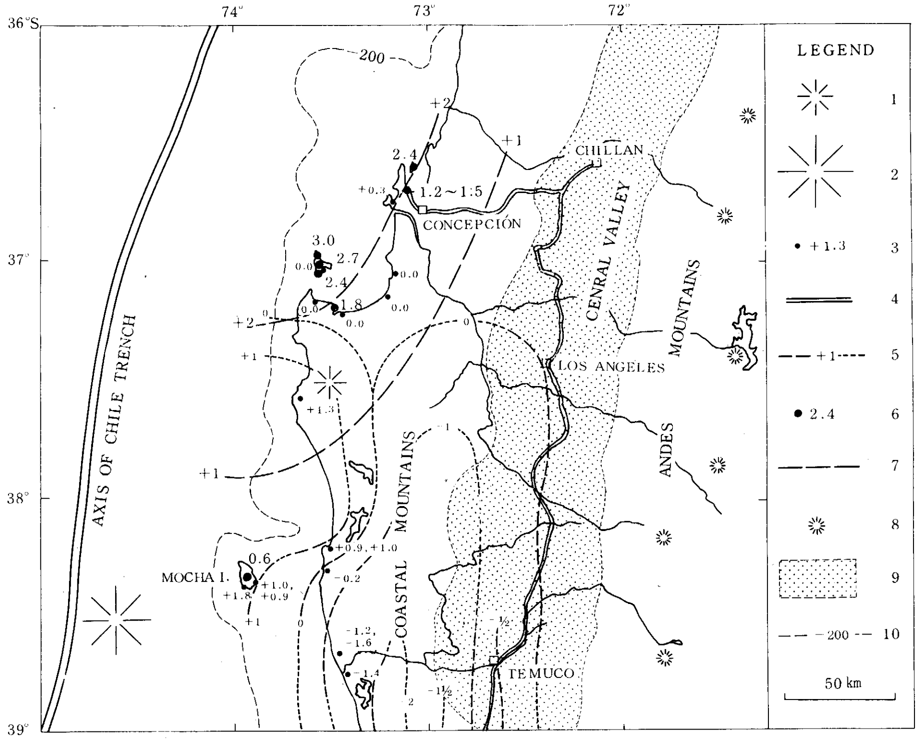

Fig. 14 Seismic crustal movements accompanied with the 1835 Concepcion earthquake and the 1960 earthquake.
1:Epicenter of the foreshock of 1960 earthquake. 2:Epicenter of the main shock of 1960 earthquake. 3:Amount of vertical displacement accompanied with the 1960 earthquake (after Plafker and Savage, 1970). 4:Leveling line along which vertical displacements accompanied with the 1960 earthquake were determined. 5:Isobase contour showing approximate amount of land-level change, in meters. Dotted where inferred (after Plafker and Savage, 1970). 6:Amount of vertical displacement accompanied with the 1835 earthquake (after Darwin, 1851 and Lomnitz, 1970). 7:Isobase contour showing approximate amount of land-level change, in meters. 8:Volcano. 9:Quaternary deposits of the Central Valley. 10:Approximate outer edge of continental shelf, depth in meters.

As seen in Fig. 14, which prepared after Plafker and Savage (1970) as for the displacement accompanied with the 1960 earthquake, not only Mocha Island but also the Arauco Peninsula except for its northern part was uplifted. The amount of uplift was relatively large in the southwestern part of the Arauco Peninsula and Mocha Island where the uplift was more than 1 meter. On the contrary, the Nahuelbuta Mountains especially its southern part, probably subsided as shown in Fig. 14, though any evidence of displacements has not been recorded for the Mountains. The northern parts of both the Arauco Peninsula and the Nahuelbuta were not affected by the earthquake-related crustal movements in 1960.

As will be mentioned in the succeeding sections, it has been noted in general that the vertical co-earthquake uplift or subsidence is followed by the opposite recovery motion during the aftershock sequence. However, as for the 1960 earthquake sequence, any evidence of the post-earthquake recovery motion opposite to the sudden co-earthquake displacement has never been noticed as far as our knowledge is concerned.

Such terms as earthquake-related, pre-earthquake, co-earthquake post-earthquake, and inter-earthquake, which are used hereinafter in this paper, are designated as illustrated in Fig. 15.

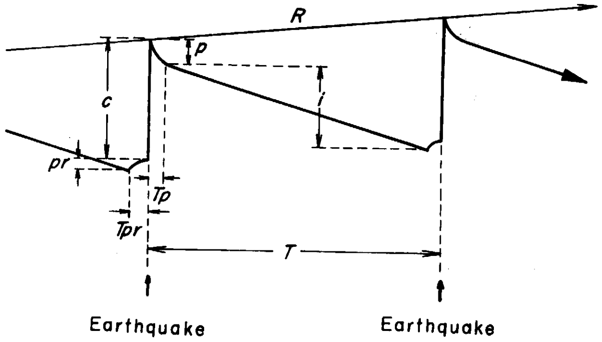

Fig. 15

Schematic diagram of earthquake-related and inter-earthquake displacements.
c:co-earthquake displacement.
pr:pre-earthquake displacement.
p:post-earthquake displacement.
$pr + c - p = e$:earthquake-related displacement.
i:inter-earthquake displacement.
T:recurrence interval.
Tpr:duration of pre-earthquake displacement.
Tp:duration of post-earthquake recovery.
$R = pr + c - p - i/T$:mean rate of vertical displacement.

2. Previous evidence of tectonic deformations associated with great earthquakes in historical time

Lomnitz (1970) made a catalogue of great Chilean earthquakes greater than 7.5 in magnitude for the period of 1562–1953. These historical data indicate that major shocks seem to have occurred periodically in almost the same regions, such as the regions off Valparaiso, off Concepción and off Valdivia. Many great earthquakes accompanying tsunamis or vertical crustal movements were located off and near the coast Besides these offshore earthquakes some great ones occurred on land between Santiago and Concepción. Crustal movements associated with these on-land earthquakes were thought to be connected with uplift of the Coast Range, but no surface fault has been observed (Lomnitz, 1970). To the south of Concepción, on the other hand, great earthquakes occurred off coast accompanying vertical uplift along the coast, instead of along the Coast Range. The area between Santiago and Concepción was thus regarded by Lomnitz (1970) as a tectonic unit different from the area between Concepción and the Chile Rise to the south.

In Fig. 16, time-space distribution of great offshore earthquakes (magnitude 8 or more) are illustrated according to Lomnitz (1970) and Kelleher (1972). As seen in this figure, in and just north of the region of this study (37°–38°S), the so-called Concepeión earthquakes occurred periodically in years 1570, 1657, 1751 and 1835 with the mean reccurence period of 92 years. In the studied region and its southern extension, the so-called Valdivia earthquakes occurred in 1575, 1737 and 1837. The 1960 great earthquake was a succeeding one of this sequence. Thus the mean reccurrence period for these four

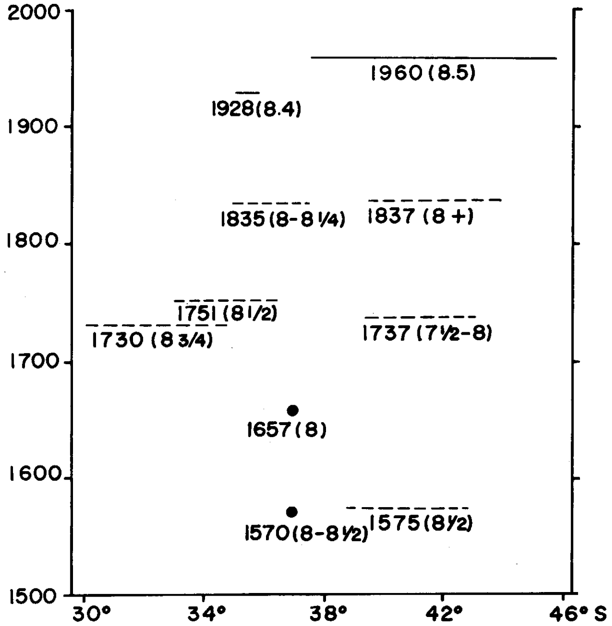

Fig. 16 Time-space diagram of Chilean major offshore earthquakes between 30° and 46°S.
The diagram is based on Kelleher (1972), the original data of which by Lomnitz (1970). Solid horizontal line segments represent the lateral extent of relatively well-determined estimates of rupture zones. Dashed lines are less reliable ones. Solid circles represent events for which no rupture zone was estimated. Numbers in the parentheses are magnitudes of earthquakes by Lomnitz (1970).

earthquakes in the Arauco-Valdivia region is 128 years. It is said that the magnitude and the areal extension of the 1960 earthquake was larger than those of the preceded two great earthquakes, but was nearly as same as those of the 1575 earthquake. It is also noticed that there seems to be a tendency of time-related occurrence between the Concepción and Valdivia earthquakes, as the cases of 1570–1575 and 1835–1837. Judging from its great magnitude and wide areal extension, the 1960 great earthquake seems to have occurred over the both focal regions at a time.

The above-mentioned historical data show that the mean recurrence interval of these great offshore earthquakes in these regions is nearly a century for recent 400 years, though the interval of Valdivia earthquakes is a little longer than that of Concepción earthquakes.

Vertical displacements associated with these earthquakes are partly documented on coasts since the 1751 earthquake (Lomnitz, 1970). At the time of the 1751 Concepción earthquake an uplift of the offshore islands was recorded, but the amounts are unknown. As for the earthquakes of 1835 and 1837, Darwin (1851) described significant vertical crustal displacements on coasts.

The amounts of uplift associated with the 1835 Concepción earthquake along the coast of the Arauco Peninsula and offshore islands are given in Fig. 14 by numerals according to

Darwin (1851) and Lomnitz (1970). Isobase contour lines for the uplift in Fig. 14 are drawn based on those amounts. The maximum uplift was reported from the northern points of Santa María Island as 10 feet. It is noteworthy that both Santa María Island and the city of Concepci´on lost a part of their uplift by the post-earthquake subsidence in the course of some weeks after the earthquake (Darwin, 1851). According to Darwin and others, Lomnitz (1970) wrote that most of the uplift accompanied with the 1835 earthquake had disappeared through a slow recovery within the period of the aftershock sequence.

Accompanying with the 1837 Valdivia earthquake 2.4 m uplift was observed at Lemus Island (44.5°S) on the ocean side of the Chonos Archipelago, but no other observations on coastal changes appear to exist.

3. Accumulation of seismic deformations in the late Quaternary

If we sum up both the vertical displacements associated with the 1835 and 1960 earthquakes affected to the Arauco region (Fig. 14) and compare it with the late Quaternary displacements of the same area (left half of Fig. 12), it is noticed that the eastward tilting in the continental shelf zone including the Arauco Peninsula is the common characteristics to both the short-term earthquake-related deformation and the long-term late Quaternary deformation, while in the Coast Range the two deformations are not similar to each other, but rather reversed. That is, the earthquake-related deformation in the Coast Range is a down-warping, but the late Quaternary deformation in the same area is, on the contrary, an up-warping as stated previously. The same fact has been pointed out by Plafker (1972) in southern Chile and Alaska in connection with the 1960 Chilean and 1964 Alaskan earthquake-related tectonic defomations, and also has been noticed by Yoshikawa (1968, 1970) in Shikoku, southwestern Japan in connection with the 1946 Nankai earthquake.

Herein let us examine a problem of accumulation of short-term displacements quantitatively, at first for vertical displacements and next for tilting.

Accumulation of vertical displacements

The amounts of vertical displacements used in the following discussion are given in Table 2, based on data obtained by previous literatures and by the present study.

The column (1) in Table 2 shows amounts of earthquake-related uplift for the latest three great offshore earthquakes in three regions; Mocha Island, the western part of the Arauco Peninsula and Santa María Island. Here p signifies the amount of post-earthquake recovery as is given in Fig. 15. The amounts for 1960 earthquake were measured in 1968 (Plafker and Savage, 1970), so these are amounts not only for pre- and co-earthquake displacements, but also contain post-earthquake displacements.

The column (2) shows mean rates of earthquake-related uplifts in historical age which were obtained by summing up the three amounts of earthquake-related uplift in (1) and then by dividing them by 200 years, nearly two recurrence periods of great earthquakes from the 1737 and 1751 earthquakes to the 1960 earthquake. However, if the displacements of the 1751, 1737 and 1657 earthauqkaes were small enough, we should use four recurrence periods, 400 years, instead of 200 years, because as mentioned above the 1575 earthquake was as large as the 1960 earthquake, and might have been accompanied by significant displacements (cf. Fig. 16). In Tables 2 and 3, the former case (200 years) is used for calculation.

The column (3) shows altitudes of late Quaternary marine terraces in the three regions

The column (4) shows mean rates of uplifts during the late Quaternary, which were

Table 2. Comparison of mean rates of vertical displacements between historical age and late Quaternary.

	(1) Earthquake-related uplift (m)	(2) Mean rate of earthquake-related uplift in historical age (m/100y)	(3) Altitude of late Quaternary terrace (m)	(4) Mean rate of uplift during the late Quaternary (m/100y)
Mocha Island	$1.0\sim1.8$ (1960) 0 (?) (1837) $0.6-p$ (1835) ($p<0.6$)	$(0.8\sim1.2)-\frac{p}{2}$	33 (Highest part of the Lower terrace; 6000y. B.P.)	0.55
Western part of the Arauco Peninsula	$0\sim1.3+$ (1960) 0 (?) (1837) $1\sim2-p$ (1835) ($p<1\sim2$)	$(0.6\sim1.6+)-\frac{p}{2}$	250 (Cañete Surface; $1\text{x}10^5$y. B.P.)	0.25
Santa María Island	0 (1960) 0 (?) (1837) $2.4\sim3.0-p$ (1835) ($p<2.4\sim3.0$)	$(1.2\sim1.5)-\frac{p}{2}$	80 (First terrace; $1\text{x}10^5$y. B.P.)	0.08

obtained by dividing the altitudes listed in (3) by each age of the terrace. Strictly speaking, for getting true mean rates of uplift, the height of sea level at the time of terrace formation is necessary to be given. We do not know the relative heights of the former sea levels, but we know that they are small relatively to the altitudes of the late Quaternary marine terraces in this region. Thus the amounts in (3) can be used for the rates of uplifting in a rough approximation. The more uncertainty lies on the age estimation of the Cañete Surface and the First terrace of Santa María Island.

From (2) and (4) in Table 2, it is apparent that the mean rates of earthquake-related uplifts in the historical time are larger than those of the late Quaternary uplift, if p is small enough. Namely, the mean rates in (2) are much larger than those in (4); 1–2 times for Mocha Island, 2–6 times for the western Arauco Peninsula, and 15–20 times for Santa María Island. These differences between amounts in (2) and (4) become smaller when amouts p are taken into consideration. The amount of p is especially of importance for the case of Santa María Island, because it is known that the co-earthquake uplift (c in Fig. 15) on the island mostly disappeared through post-earthquake recovery (p) whithin the period of the after shock sequence as cited before. For the cases of Mocha Island and the western Arauco Peninsula the amounts of p are unknown. Thus the difference between amounts in (2) and (4) may be due partially to uncertainty in amounts in (1) and (3), and partially to the existance of inter-earthquake subsidence (amount i in Fig. 15).

In the case of Muroto Promontry, southeastern Shikoku, Japan, it has been known that the radio $(p + i/pr + c)$ of the total recovery $(p + i)$ to the pre- and co-earthquake uplift $(pr + c;$ pr may be small) in one recurrence time is 4/5; in other words, the ratio of the residual displacement to the pre- and co-earthquake ones $(pr + c - p - i/pr + c)$ is 1/5 (Yoshikawa et al., 1964 a, b,). Muroto Promontory has been the only place in the world where these ratios were known in success.

Then, if we assume for the cases of Mocha Island and the western part of the Arauco Peninsula that:

1) amounts p are negligibly small, i.e., amounts in (2) represent mean amounts of $pr + c$,
2) amounts in (2) and (4) are reliable enough,
3) the mean rates of uplift for the short-term which are shown in (2) are equal to the mean rates for the long-term shown in (4), and
4) amounts pr are negligibly small,
then we can obtain the ratio of the residual displacement to the co-earthquake one $(pr + c - p - i/pr + c \fallingdotseq c - i/c)$ through dividing amounts in (4) by amounts in (2). The results obtained are: 1~1/2 for Mocha Island and 1/2~1/6 for the western Arauco Peninsula.

Accumulation of earthquake-related tilting

The amounts for tiltings are given in Table 3, based on data from previous literatures and our measurements and calculations.

Table 3. Comparison between mean rate of historical earthquake-related tilting and that of the late Quaternary tilting.

	(1) Earthquake-related eastward tilting	(2) Mean rate of earthquake-related eastward tilting in historical age (per 100y)	(3) Eastward inclination of late Quaternary terrace surface	(4) Mean rate of eastward tilting during the late Quaternary (per 100y)
Mocha Island	$4\sim5\mathrm{x}10^{-5}$ (1960) 0 (?) (1837) ? (1835)	$2\sim2.5\mathrm{x}10^{-5}$	$2\sim4\mathrm{x}10^{-2}$ (Higher terrace; $6\sim8\mathrm{x}10^{4}$y)	$3\sim6\mathrm{x}10^{-5}$
Western part of the Arauco Peninsula	$5\sim6\mathrm{x}10^{-5}$ (1960) 0 (?) (1837) $1\sim2\mathrm{x}10^{-5}$ (1835)	$3\sim4\mathrm{x}10^{-5}$	$0.5\sim1\mathrm{x}10^{-2}$ (Cañete Surface; $10\mathrm{x}10^{4}$y)	$0.5\sim1\mathrm{x}10^{-5}$
Santa María Island	0 (1960) 0 (?) (1837) $2\sim3\mathrm{x}10^{-5}$ (1835)	$1\sim1.5\mathrm{x}10^{-5}$	$2\mathrm{x}10^{-2}$ (Third terrace; $5\mathrm{x}10^{4}$y)	$4\mathrm{x}10^{-5}$

The column (1) in Table 3 shows amounts of earthquake-related eastward tilting for the three regions as in the case of Table 2. As for the amounts of 1835 earthquake, some corrections must be necessary in connection with amounts p in Table 2, but we have no data for these corrections, hence we tentatively regard them as the approximate amounts of earthquake-related tilting.

The column (2) shows amounts of mean rates of earthquake-related eastward tilting in the historical age, which were obtained by the same procedure as in the case of Table 2.

The column (3) shows amounts of eastward inclinations of the late Quaternary terrace surfaces which were measured in this study.

The column (4) shows amounts of mean rates of eastward tilting during the late Quaternary, which were calculated by dividing the inclinations in (3) by each age of terrace. Herein the given age for the Third terrace in Santa María Island is very tentative.

Comparing (2) and (4) in Table 3, it can be said that the mean rates of (2) and (4) for each region are same in a rough approximation. As to Mocha and Santa María Islands amounts of (2) are smaller than those of (4), contrarily to the cases in Table 2.

A proposal of two seismo-tectonic zones

Through the above-mentioned comparisons of uplift and tilting between the short term historical age and the long-term late Quaternary period, it is concluded that the displacement or deformation of the earth's crust in the continental shelf zone has been accumulated for the past 10^3-10^5 years at the same rate in order and with the same mode of deformation as those in historical age. In other words, the continental shelf zone seems to have been deformed for at least 10^5 years by the accumulation of co-earthquake deformations. Thus, the continental shelf zone in this region can be understood as a zone where secular deformation through recent geologic time has been co-earthquake deformation as revealed in historical age. In this sence, we designate such tectonic zone as the continental shelf zone in this region *a zone of co-earthquake deformation*. The accumulation of co-earthquake deformation should be explained in connection with the elastic rebound theory for earthquake, on which we will devote a discussion in a separate paper.

On the other hand, in the Nahuelbuta Mountains the mode of acute co-earthquake deformation is a downwarping, and it is reverse to the mode of long-term Quarternary deformation, which is an upwarping as mentioned in the foregoing sections. Consequently, it is quite likely that in the mountains the inter-earthquake deformation has a mode similar to the Quaternary deformation of upwarping, and amounts of this inter-earthquake upwarping is superior to those of co-earthquake downwarping. Thus the resultant upwarping deformation during an earthquake recurrence time would have accumulated for long time so as to make the Nahuelbuta Mountains. If this line of thinking is correct, the term *a zone of inter-earthquake deformation* can be applied to the mountains, a part of the Coast Range of central Chile.

V. SUMMARY

This work has been carried on as a study on the Quaternary crustal movements in the outer part of the outer arc near a trench, where great earthquakes have frequently been experienced. The main results obtained in and near the Arauco Peninsula, central Chile, are as follows.

1) In the Nahuelbuta Mountains there are low relief surfaces formed during the late Tertiary probably under subaerial denudation. The features of the surfaces indicate that an upwarping has occurred in the mountains with the N-S and NW-SE trending axes of uplift during the Quaternary.

2) The topography of the Arauco Peninsula and the western border of Nahuelbuta Mountains is subdivided into five geomorphic surfaces: the Las Nochas, Buena Esperanza, Cañete, Lower terraces, and Holocene lowland surfaces, of which the former three are marine terraces, and the later two are partly alluvial and partly marine in origin. Our field studies of their elevated coastal features and terrace deposits lead us to a conclusion that the formation of each surface was made under a marine transgression, probably caused by the eustatic rise of sea level during either an interglacial, or an interstadial and a postglacial age. The widest Cañete Surface is presumably ascribed to the last great interglacial age.

3) Four Pleistocene marine terraces are distinguished on Santa María Island and two terraces on Mocha Island. Their eastward tiltings in the late Quaternary are revealed by altitudes of elevated shorelines and also by inclinations of the terrace surfaces.

The radiocarbon datings of Holocene terrace deposits on Mocha Island give a mean rate of uplift as 55 cm per 100 years for the last several thousands years which seems to be one of the most rapid rate of land uplift in the world except for the rates reported from the regions which had been coversed by ice sheets in the Pleistocene.

4) The mode of Quaternary crustal movements in and near the Arauco Peninsula is a tilting or warping without any faulting on land. The continental shelf zone, including the Arauco Peninsula, Santa María and Mocha Islands, has been tilted to the east that is, landward as a whole, and partially has been upwarped with a NW-SE trending axis in the central part of the Arauco Peninsula. Our morphological studies disclose that this upwarping became active at latest after the formation of erosional surfaces in the Nahuelbuta Mountains and has continued to after the formation of the Cañete Surface.

The eastward tilting of the shelf zone in the Quaternary Period is markedly different from the mode of crustal movements in the Paleogene and Neogene Periods in which a predominantly westward tilting indicated by the structure of Eocene and Miocene strata. Inference is that a change occurred in the Pliocene Epoch in the mode of crustal movement.

5) This region has been attacked nearly once in every century by great earthquakes of magnitude 8 or more such as the so-called Valdivia and Concepción earthquakes. No substantial difference is found between the mode of regional, acute co-earthquake deformation and that of the long-term Quaternary eastward tilting, so far as the shelf zone is concerned. Besides in the shelf zone the mean rate of the co-earthquake tilting in the historical age is of as the same order as that in the late Quaternary. Therefore, the term *a zone of co-earthquake deformation* can be applied to the continental shelf zone in this region.

In the Nahuelbuta Mountains, however, the mode of long-term Quaternary deformation is rather reversed to the co-earthquake deformation. Thus it is very likely that the inter-earthquake deformation, instead of the co-earthquake deformation, has been accumulated through the Quaternary in the Nahuelbuta Mountains. So we give the term *a zone of inter-earthquake deformation* to the Nahuelbuta Mountains

In the shelf zone, the ratios of the residual displacement to the co-earthquake displacement in an earthquake recurrence time were estimated under some assumptions at 1/1~1/2 for Mocha Island, and 1/2~1/6 for the western Arauco Peninsula. This implies that the ratio varies from place to place even in not a so great distance.

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Photographs

Photo 1 Scenery from the central southern part of the Arauco Peninsula (northwest of Cañete town) to the east. The mountains, which show low-relief crest lines, are the Nahuelbuta. At the central right, the highest peak of the mountains is seen. The flat foreground surface is the Cañete Surface. Low gentle mounds on the surface are longitudinal sand dunes. Between the mountains and Cañete Surface, the higher terraces are seen at left half.

Photo 2 The Las Nochas Surface (left) and the Nahuelbuta mountains (right). The boundary angle between them is the elevated shoreline of the Las Nochas Surface. The photographer is standing on the elevated shoreline, 486 m high above sea level, 8 km southeast of Curanilahue.

Photo 1

Photo 2

Photo 3 Whitish eolian sand (eolianite, lower) and brown loamy soil (upper) on the Cañete Surface. Fossil burrows are seen in the uppermost part of the eolian sand bed, which consists of the upper part of the Cañete Formation.

Photo 4 The middle horizon of this road cut is the fluvial sand bed overlying the uppermost Cañete Formation. The base of the fluvial bed shows small three channels, which are filled with muddy deposits including pebbles. An eolian bed of about 1 meter in thickness overlies the fluvial deposits. Photographed at 6 km north of Cañete town.

Photo 3

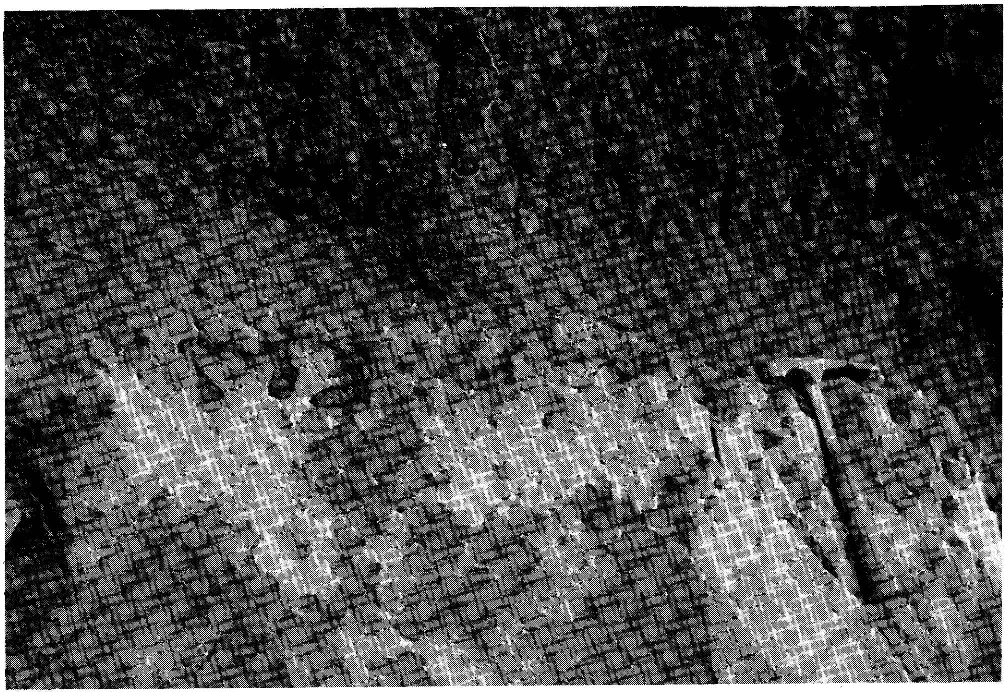

Photo 4

Photo 5 The mouth of River Lebu, western coast of the Arauco Peninsula. The flat skyline shows the Cañete Surface reaching about 200 m high above sea level here. The town of Lebu is located on the Holocene alluvial lowland, which seems to be composed of thick alluvial deposits filling a drowned valley.

Photo 6 A view of the southern coast of the Arauco Peninsula. The scarp at the left is an ancient sea cliff bordering the Cañete terrace. The sand dunes are partly active and partly fixed by grasses and shrubs, especially along streams.

Photo 5

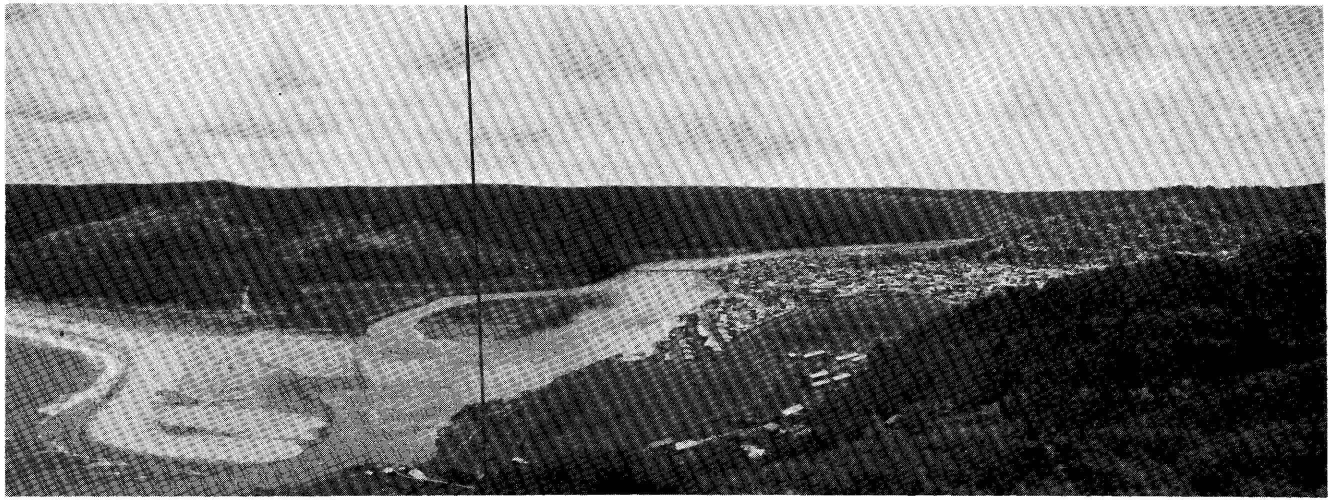

Photo 6

Photo 7 A view of the southern part of Santa María Island toward south. The flat surface is the Third terrace, 20–60 m high above sea level. This surface inclines from the right (west) to the left (east). Two hills in the central part may be composed of the lower sedimentary unit. The mountains behind these hills are the northwestern mountains of the Arauco Peninsula.

Photo 8 The northeastern coast of Mocha Island seen from the pier at Caleta La Hacienda. White beach sand divides the Holocene Lower terrace and the rock bench in the foreground, which was uplifted above sea level at the time of 1960 earthquake.

Photo 7

Photo 8

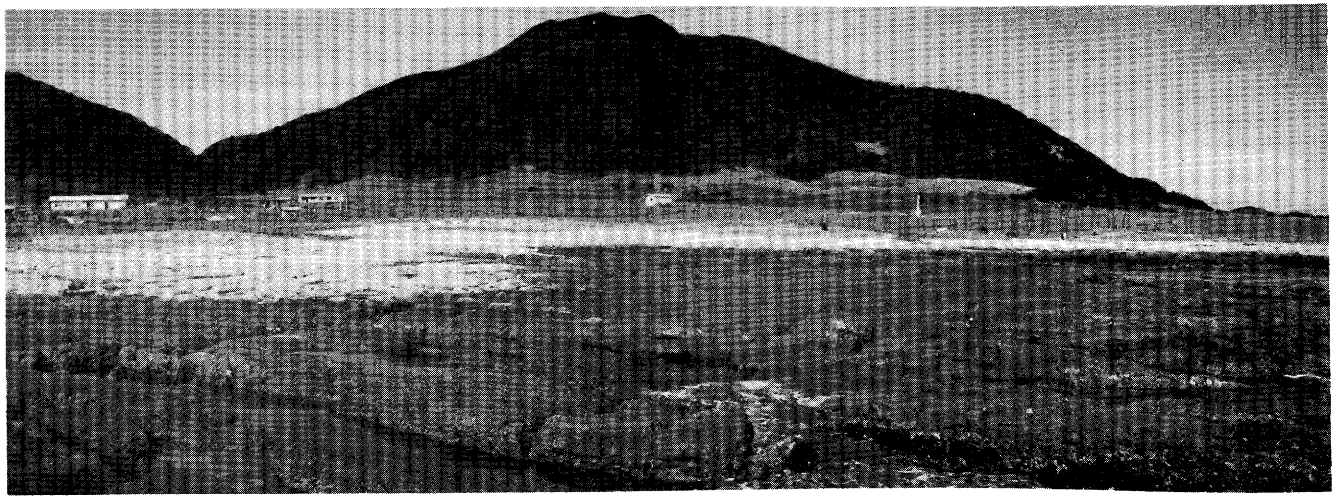

Photo 9 An air view of the eastern half of Mocha Island. The steep ancient sea cliff separates the mountains and the flat Lower terrace, an uplifted abrasion platform. On the Lower terrace, a pattern of elevated beach ridges is seen. Note the flatness of the crests of the mountains, which represents the existance of the Higher and Middle terraces.

Photo 10 Beach deposits on the Lower terrace of Mocha Island, consisting of mainly sand, pebbles and shell fragments. Such shell fragments were used for radiocarbon dating. The surface soil is thin

Photo 9

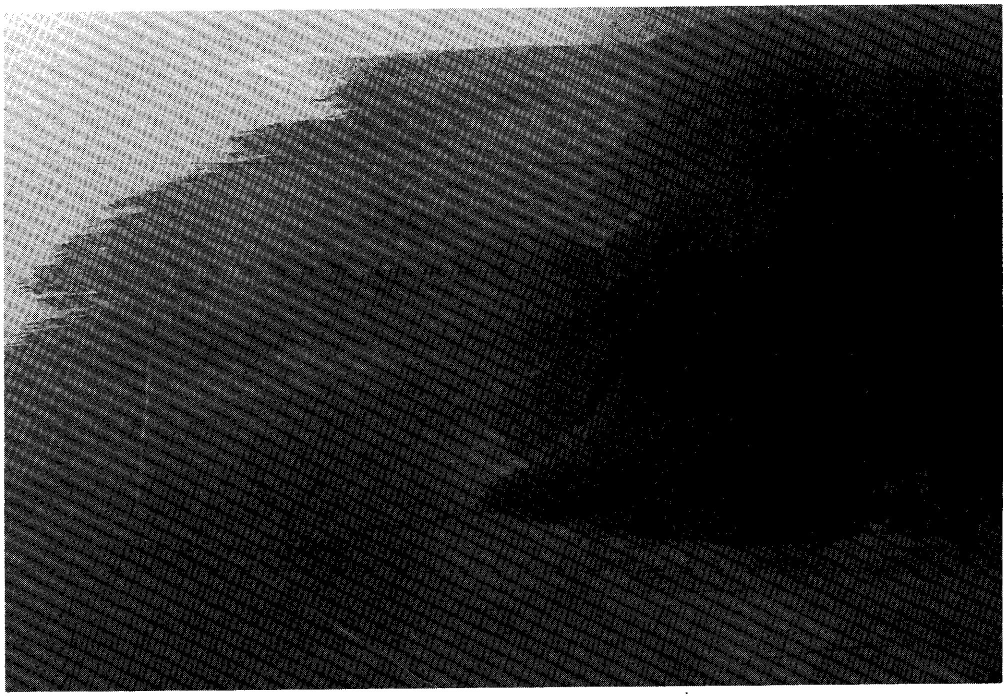

Photo 10