Fast Holocene uplift rates at the Andes of Chiloé, southern Chile

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ABSTRACT

Seven ^{14}C ages on shell material from elevated beaches in the Andes of Chiloé (42-43°S) indicate ages varying from 420±80 to 3,130±80 yr B.P. Estimated elevations of the sampled localities show that uplift of the order of 10 m/ka has affected the region. In this segment of the Andes, where amounts of coseismic uplift/subsidence of the order of 1 m were observed during the 1960 earthquake, the east-west distribution of the measured uplift rates is probably related to late Holocene coseismic deformation. Uncertainties concerning the contribution of postglacial isostatic rebound on paleo sea level and on the water depth at which the dated shells lived do not invalidate this conclusion. Uplift is probably related to the Liquiñe-Ofqui Fault Zone which crosses the area.

Key words: Elevated shell beds, Late Holocene, ^{14}C dating, Fast uplift, Chiloé, Chile.

RESUMEN

Alzamiento holoceno rápido de la Cordillera de los Andes en Chiloé, sur de Chile. Siete edades C^{14} en conchas de terrazas marinas elevadas en los Andes de Chiloé, indican edades entre 420±80 y 3.130±80 años A.P. Las alturas estimadas para las localidades en que se tomaron muestras permiten establecer tasas de alzamiento hasta del orden de 10 m por mil años. En este segmento de los Andes, en el cual se midieron alzamientos/subsidencias cosísmicas del orden de 1 m durante el sismo de 1960, la distribución este-oeste de las velocidades de alzamiento determinadas en este trabajo, permite relacionarlas con deformación cosísmica holocena. Si bien los efectos del eventual alzamiento por rebote isostático glaciar en el área estudiada no han sido cuantificados, y no se conoce con seguridad la profundidad del agua en que vivieron los organismos datados, ello no parece invalidar las conclusiones de este trabajo. El alzamiento está relacionado, probablemente, con la Zona de Falla Liquiñe-Ofqui que cruza el área.

Palabras claves: Terrazas marinas, Holoceno superior, Datación C^{14}, Ascenso rápido, Chiloé, Chile.

INTRODUCTION

Geologic mapping of the Chiloé mainland, during 1988-1990 by FH, resulted in the discovery of several shell deposits in low altitude terraces. Shell bearing elevated deposits were also observed and sampled on Isla de Chiloé (Chiloé Island). ^{14}C dating of fossil shells yields late Holocene age for the terraces. ^{14}C

Revista Geológica de Chile, Vol. 20, No. 1, p. 15-23, 4 Figs., 1 Table, July 1993.

dating was carried out at the Laboratory of Gakushuin University, Japan, in 1990. Elevations were hand level measurements above estimated high tide water level based on onsite observation of the present day beaches. The purpose of this paper is to call attention to the existence of these raised shell horizons, previously unreported. A preliminary determination of uplift rates and an assessment of their geological significance will be given.

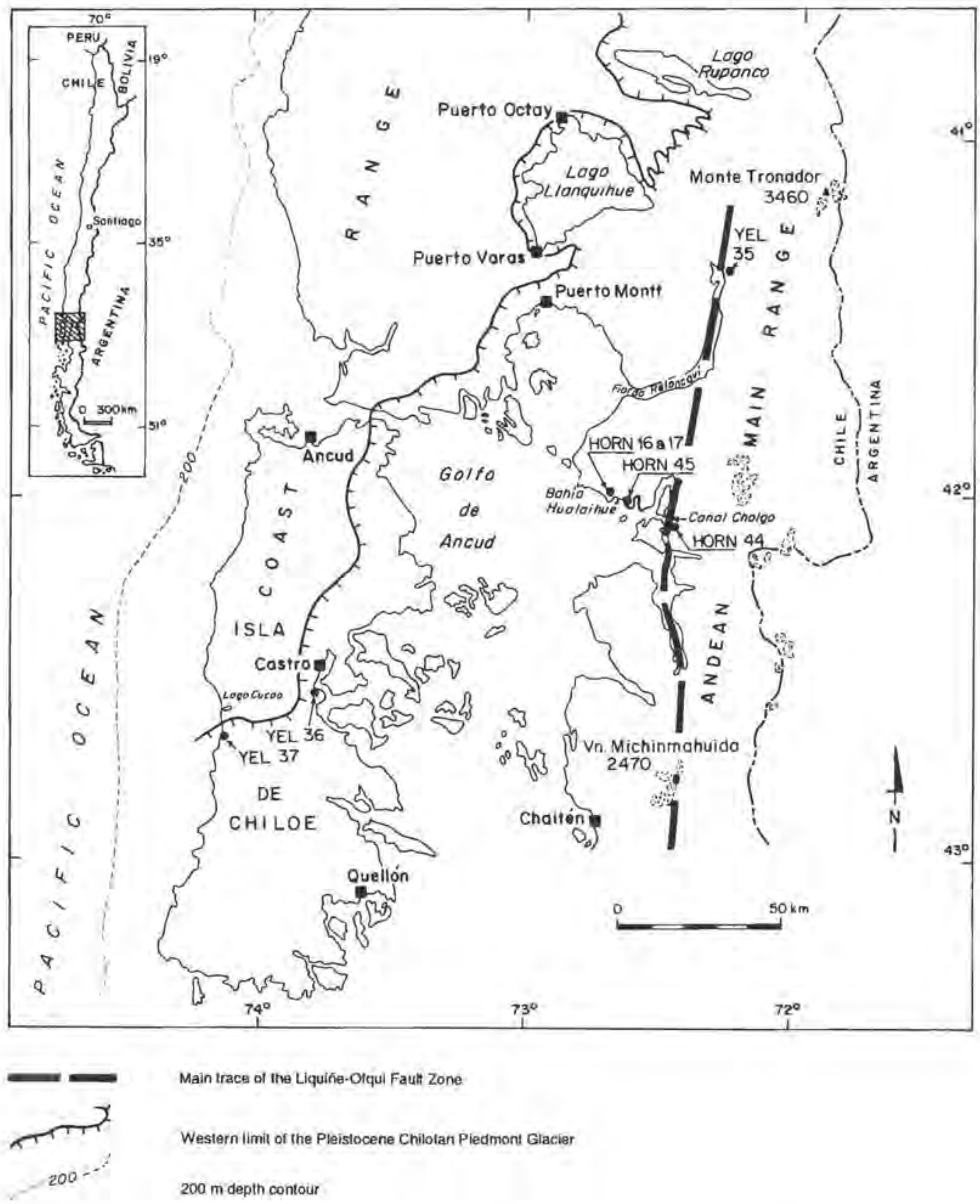

FIG.1. Sample location map with indication of the western limit of the Chilotan Piedmont Glacier after Heusser (1990) and the main trace along the Liquiñe-Ofqui Fault Zone.

GEOLOGICAL BACKGROUND

In this segment of the continental margin, three main morphological units are distinguished: from west to east these are the Coast Ranges, the Ancud Gulf and the Main Andes Range.

The Coast Ranges consist mainly of metamorphic rocks of the late Paleozoic accretionary prism, which crop out continuously on the coast of Chile south of 34°S. They are covered locally by Tertiary sedimentary and volcanic deposits and by Pleistocene glacial sediments.

The Golfo de Ancud (Ancud Gulf) is the southern continuation of the Central Valley of Chile, a tectonic depression whose floor is here below sea level. The Main Range mainly consists of the North Patagonian Batholith, which ranges in age from Cretaceous to Pliocene. Strips of metamorphic rocks of the accretionary complex crop out in the vicinity of the Liquiñe-Ofqui Fault Zone, a major trench-linked dextral strike-slip structure active from the Eocene to the Pliocene and possibly to the Holocene. Eocene-Miocene volcaniclastic strata also crop out nearby.

The area was covered by Pleistocene glaciers with a maximum thickness of 1,000 m, whose last major retreat occurred close to 13,000 years ago (Heusser,1990).

The Andes are located over a seismically active Benioff Zone, which in Chiloé is generated by the subduction of the oceanic Nazca plate beneath South America. Chiloé is situated halfway along the 1,000 km rupture zone which generated the Ms= 8.5 1960 earthquake in Chile. Plafker and Savage (1970) presented data on the land level changes which occurred in association with this earthquake. The Isla de Chiloé subsided more than one meter in Ancud, while the eastern coast of the Golfo de Ancud was uplifted by up to 0.5 m. The hinge line of deformation apparently ran north midway along the Golfo de Ancud. Barrientos *et al.* (1992) have shown evidence that 1 m of postseismic uplift has occurred near this hinge line since 1960, as indicated by mareographic measurements at Puerto Montt.

The land level changes related to seismic activity are very probably not the only ones to have taken place in Chiloé. As indicated above, Holocene deglaciation probably has triggered glacioisostatic rebound movements in the area. However, no factual data demonstrate the amplitude or rate of these movements in the area. As a reference, in Scandinavia a 10 mm/yr long term rebound is taking place at present, and at Glacier Bay, Alaska (Hicks and Shofnos,1965) a 39 mm/yr uplift occurs related to present localized deglaciation.

DESCRIPTION OF SAMPLED SITES

Seven samples of shells were obtained from the localities shown in figure 1. ^{14}C ages obtained are shown in table 1 together with other data to be discussed below.

BAHIA HUALAIHUE (HUALAIHUE BAY)

Samples HORN 16 and HORN 17 were collected at the western coast of Bahía Hualaihué (also called Bahía 'Gualaihué'). HORN 16 comes from a road cut which exposes a layer of clams in living position, *i.e.*, most of the shells are closed with both valves present. It is covered by a thin layer of shell fragments embedded in a dark fine-grained matrix over which a thin soil layer has developed (Fig. 2). ^{14}C age of the shells which are 3 m above sea level is 750±80 yr B.P.

HORN 17 was collected in an outcrop about 50 m inland from HORN 16, at 10 m above sea level, in what appears to be a remnant of a thick layer of shells in which different species, mostly clams and *Mytilus*, are present. ^{14}C age of these shells is 2,050±90 yr B.P. The outcrops are separated by a gentle slope covered by grass.

HORN 45 was collected from the eastern shore of Bahía Hualaihué, 4 km east of HORN 16 and 17. In the present sea cliff, 4 m above sea level (Fig. 3a) a shell bed with clams in living position is lying on top of a coarse-grained deposit probably of glacio-fluvial origin.

This deposit shows a wedge structure filled in with finer grained sediments, probably a periglacial ice wedge developed before the deposition of the shell bed. The ^{14}C age of these shells is 430±80 yr B.P. Over the shell bed, a thin layer of soil has developed in what constitutes the present day ground surface.

TABLE 1. RADIOCARBON DATED HOLOCENE SHELLS OF CHILOE AND DIFFERENT CALCULATIONS ON UPLIFT RATES AS INDICATED IN THE TEXT.

1 Sample number	2 Code number	3 ^{14}C age[1] yr B.P.	4 Altitude m a.s.l.	5 Uplift rate[2] m/ka[5]	6 Uplift rate[3] m/ka[5]	7 Elevation change in 1960 (m)	8 Uplift rate before 1960 in ka[5]	9 Shell species
HORN 16	GaK-15004	750±80	3±1	4.0	5.0	+0.5	4.3	*Protothaca sp.*[4]
HORN 17	GaK-15005	2,050±90	10±2	4.9	5.9	+0.5	5.6	*Protothaca thaca*
HORN 44	GaK-15006	360±80	10±2	27.8	n.d.*	n.d.*	n.d.*	*Protothaca sp.*[4]
HORN 45	GaK-15007	430±80	4±1	9.3	10.3	+0.5	9.1	*Protothaca thaca*[4]
YEL 35	GaK-15008	3,130±80	30±5	9.6	10.6	n.d.*	9.6	*Protothaca thaca*
YEL 36	GaK-15009	1,960±80	6±1	3.1	4.1	-1.5	4.8	*Protothaca thaca*
YEL 37	GaK-15010	420±80	3±1	7.1	8.1	-1.0	10.5	*Mesodesma donacium*[4]

[1] based on Libby's half life (5,700 years)
[2] with constant sea level
[3] with sea rise at 1m/ka
[4] in growth position
[5] ka 1,000 years
* not determined

FIORDO RELONCAVI (RELONCAVI FJORD)

Sample YEL 35 was obtained from a road cut on the road connecting Ralún with Cochamó,1 km south of the bridge over the Ralún river. The altitude of the sampling point was determined as 30 m by Thiele *et al.* (1986). The exposed stratigraphy of this road cut (Fig. 3b) consists of: **a**- a basal dark fine-grained layer with small shell fragments; **b**- a layer composed of 90% clam and *Mytilus* shell fragments, embedded in a dark matrix, with some wood fragments and 5-8 cm angular pebbles; and **c**- a sandy, finely laminated horizon, with cross bedding and varve like intervals. The shell sample is dated at 3,130±80 yr B.P.

CANAL CHOLGO (CHOLGO CHANNEL)

In a road cut between Hornopirén and Cholgo, on the east coast of Canal Cholgo, a small outcrop of a shell bed occurs. No stratigraphy is observed, so there is no clear indication that the site is not an anthropogenic shell mound. Sample HORN 44 from this locality,10 m above sea level, was dated 360±80 yr B.P., and it will not be considered further in this paper.

ISLA DE CHILOE

YEL 36 comes from a road cut just beside the sea at the locality of Nercon,7 km south of Castro. The shell bed occurs (Fig. 3c) at 6 m altitude, lying on top of a dark fine-grained bed with organic matter and a fluviatile conglomerate with sandy matrix. Shells are dated at 1,960±80 yr B.P.

YEL 37 was collected from a natural outcrop on a river bank at the western part of Lago Cucao (Cucao Lake), near the Pacific Ocean. The clam shells form a layer 3 m above sea level, many are in living position, lying over a layer of poorly consolidated sand with some coarse conglomerate lenses (Fig. 3d).These shells are dated at 420±80 yr B.P.

ALTITUDE AND AGE DATA

The altitudes of the sampled shell beds were estimated with a hand level; datum was taken at high tide level as indicated by inspection of the present day beaches. The altitudes given are certainly most accurate for samples collected in cliffs which are in the immediate vicinity of the sea (HORN16, HORN 45, YEL 36, YEL 37) where the maximum possible error is estimated at *ca.* 1 m. They are progressively less accurate for the two localities which are presently farther away from the sea (HORN 17, YEL 35). HORN 17 is 50 m inland and an error of ± 2 m can be estimated as a maximum. YEL 35 is at an altitude of 30 m after Thiele *et al.* (1986) who did a detailed geological mapping of the area. A maximum error of *ca.* 5 m is reasonable. HORN 44 is not considered further, because it is suspected to be an anthro-

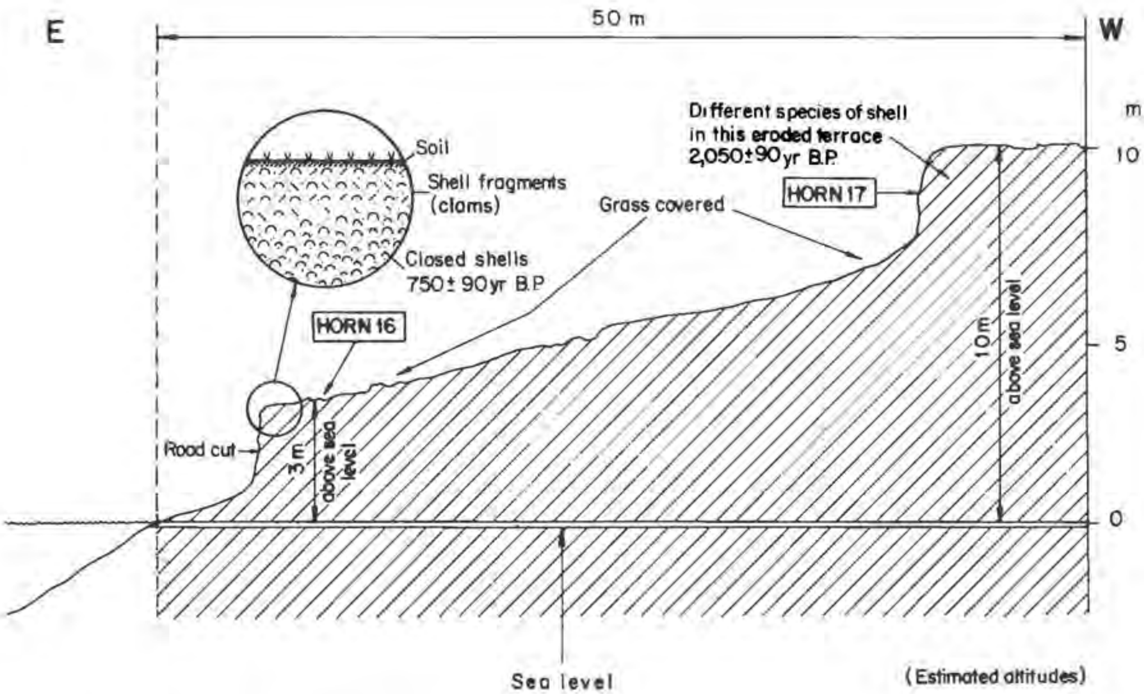

FIG. 2. Schematic cross section at the western coast of Bahía Hualaihué.

pogenic shell mound. It also gives unreasonable uplift rates in table 1.

The sampled fossil shells are regarded as having grown in very shallow water, probably at the intertidal environment. This statement is based on the similarity of the sampled deposits, particularly at Bahía Hualaihué and at the coast near Lago Cucao with the present association of mollusks in the immediate vicinities, which are living in the intertidal zone. As altitudes were measured with respect to high water level, and if the sampled shells lived in deep water as apparently can be the case with *Protothaca* (R. Paskoff, written communication, 1992), the calculated uplift rates (see below) would be somewhat too low.

With respect to the ^{14}C dating, no water reservoir correction (WRC) has been attempted. The effect on the ages of WRC is thus unknown, except for the probable effect it would have of 'aging' the samples. Also, it is probable that the correction would be different for the shells that lived in closed bays or fjords, from those that lived in open ocean localities as Cucao. If this correction is not considered, then the estimated uplift rates are minimum bounds for each site.

UPLIFT RATES

The raw altitude and age data (Table 1; columns 3, 4) give rapid uplift rates in the area for all the samples, varying from 3.1 to 9.6 m/ka (Table 1, column 5). These uplift rates should be considered as minimum rates as explained above, because of the lack of WRC correction and uncertainty about ancient water depth below the high tide reference level herein adopted. Unfortunately these corrections cannot be quantified with the available data set.

The uplift rates in column 5 have been calculated assuming a constant sea level. However, if a sea level rise of 1 m/ka for the time span is considered (Lajoie, 1986), the uplift rates are increased to the values presented in column 6 which still should be considered as minimum uplift rates.

The altitude changes produced by the 1960 earthquake, from Plafker and Savage (1970), are shown in table 1, column 7. If their effect is removed, a pre 1960 set of uplift rates can be calculated, as shown in table 1, column 8.

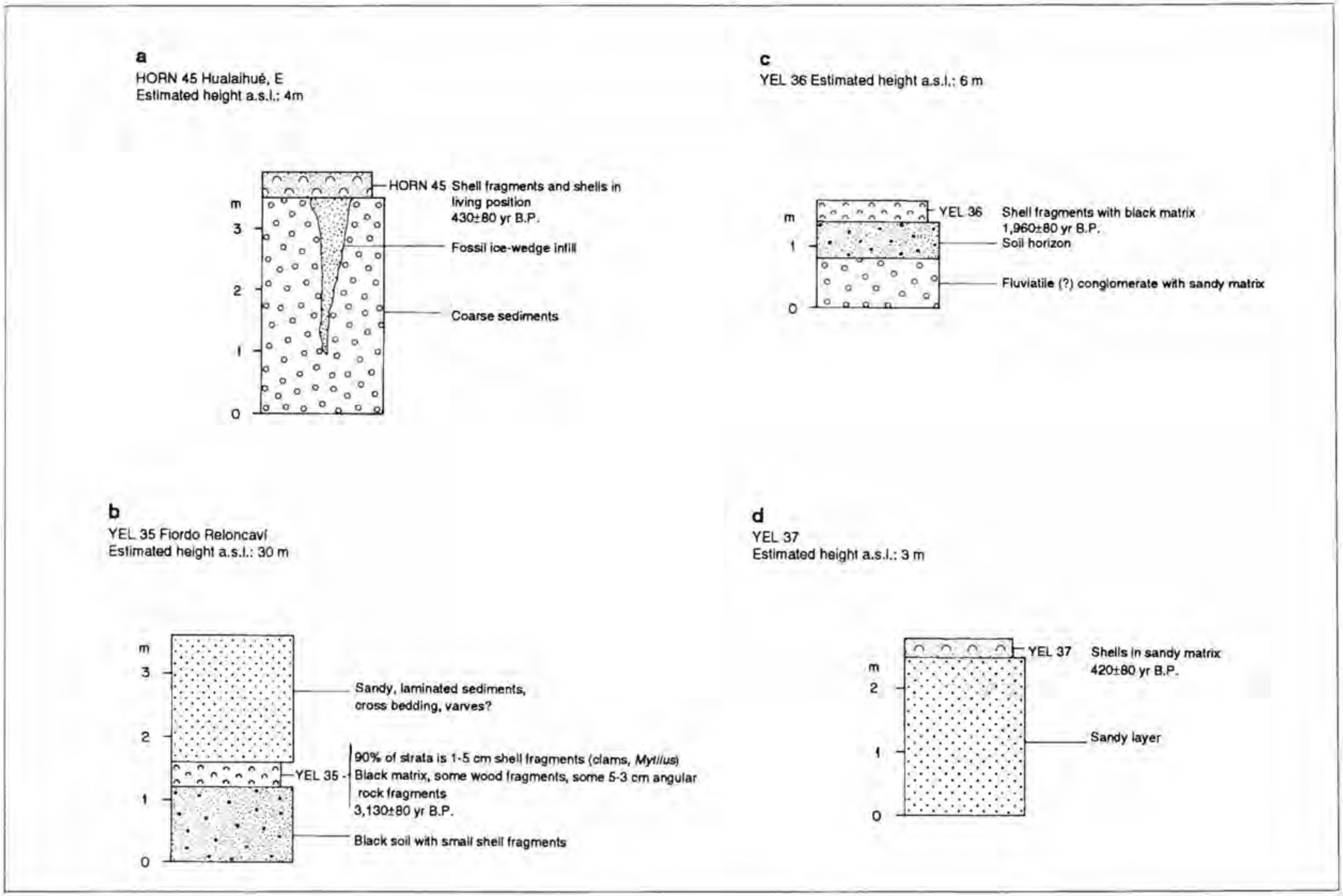

FIG.3. Stratigraphy observed at: **a**- HORN 45; **b**- YEL 35; **c**- YEL 36, and **d**- YEL 37 sampling sites.

Barrientos *et al.* (1992) have shown that 1 m of postseismic uplift has occurred at Puerto Montt since1960. If this uplift is homogeneous over the studied area, the uplift rates would have to be modified accordingly. However, the variation in space of the postseismic uplift is not known and will not be considered here.

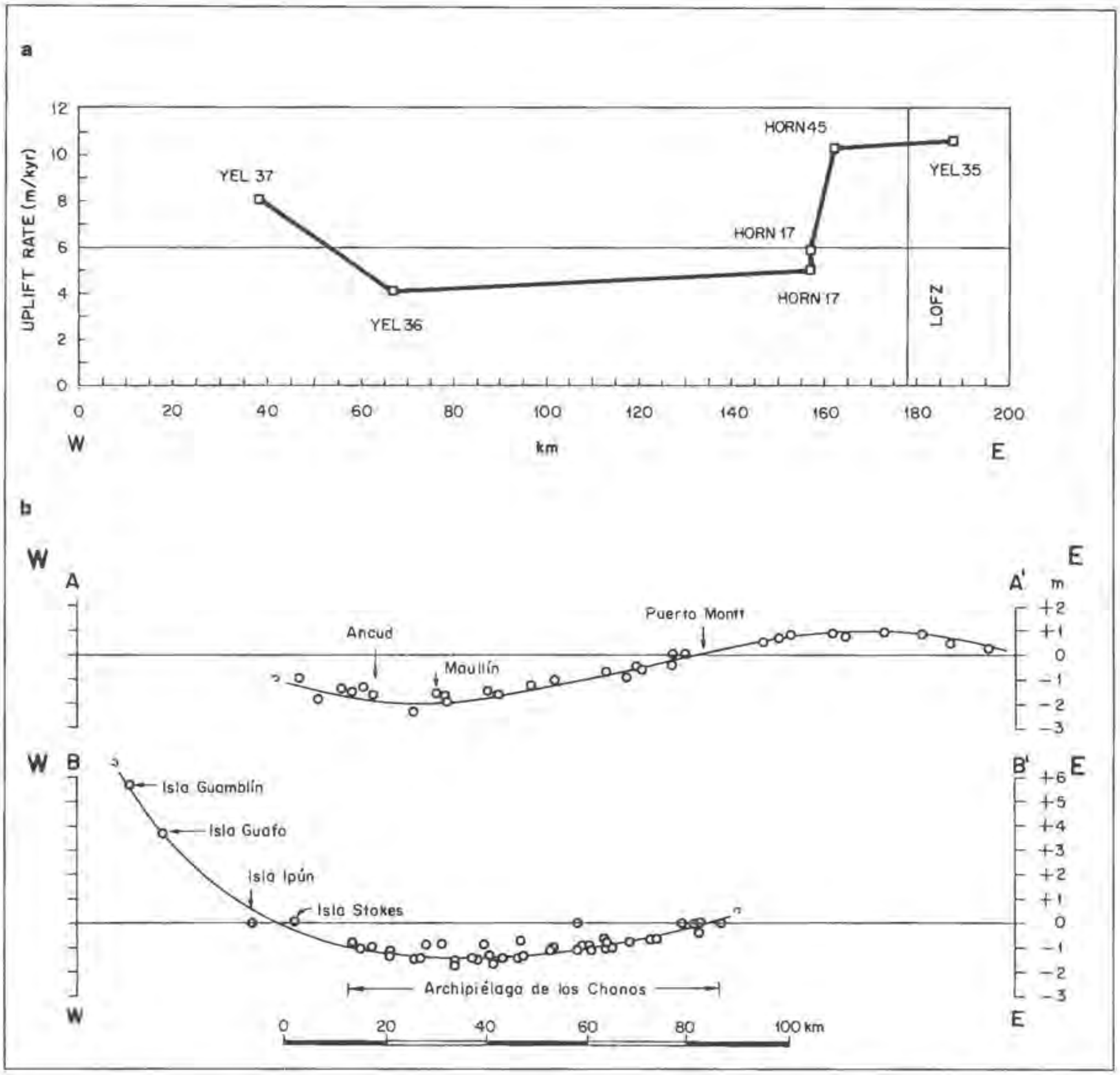

FIG. 4. a- schematic east-west cross section of the area showing net uplift rates of table 1 *versus* distance of the sample localities to the -200 m submarine depth contour with the data obtained in this paper; b- east-west cross sections (from Plafker and Savage,1970) showing coseismic altitude changes associated with the 1960 earthquake. A-A' is near the northern part of the area shown in figure 1. B-B' is about 50 km south of the area shown in figure 1. Note that section AA' is N97,5°E and not, N90°E as the section in figure 4a.

DISCUSSION

The studied sector of the Andes bears evidence of relative land-sea height instability in the late Holocene and up to the present. Coseismic and postseismic altitude variations are well docu-mented.

However, the effect of postglacial isostatic rebound still must be evaluated. Assuming an initial thickness of ice of 1 km, isostatic equilibrium requires that the crust be depressed approximately 300 m. If the ice load were removed suddenly 13,000 years ago, uplift should occur as the depression relaxes exponentially to zero. Following McConnell (1968), relaxation ti-mes for this process might range from 1 to 10 ka with the smaller figures being appropriate for loads of smaller geographic extent. The choice of relaxation time is critical. For instance, if the relaxation time is 10 ka, then about 82 m of uplift still remain to be accomplished, and uplift should be going on at the present time at a rate of about 8.2 m/ka (8.2 mm/yr). This does not fit uplifted-shell data well at all. However, if the proper relaxation time is 1 ka, then essentially all glacial rebound has been accomplished in the area, and all current uplift can be attributed to tectonic causes. Judging from the younger horizons reported on in table 1, uplift for the past 2 ka has been going on at a nearly linear rate of 4 m/ka. Perhaps part of the excess uplift observed at YEL 35 (30 m for approximately 3 ka) is isostatic, but it is not possible to assure this hypothesis.

If the uplift rates are projected into an east-west transversal section at latitude 42°S as in figure 4a, which has an arbitrary western starting point at the 200 m depth contour, it is possible to observe greater uplift rates at the western coast of Isla de Chiloé, and in the samples which are near the main trace of the Liquiñe-Ofqui Fault Zone. This trend is similar to the one caused by the deformation observed by Plafker and Savage (1970) to have accompanied the 1960 earthquake in the area, shown in figure 4b for comparison. This similarity is interpreted as indicating that the observed late Holocene uplift rates are controlled by the coseismic deformation in the area; glacioisostatic rebound of a broader area would constitute a common background of unknown, but probably small magnitude, over which the coseismic deformation is being measured.

Thiele *et al.* (1986) noted a high uplift rate since the Miocene for the area around Fiordo Reloncaví, based on the exposure of granitoids and metamorphic country rocks emplaced or generated more than 6 km deep in the crust. These authors bracket the mean uplift rates between values of 0.6 and 2 km/Ma (2m/ka). They also suggest from the present altitude of the shell beds at Fiordo Reloncaví (YEL 35) that in the Holocene the uplift rate at that locality must have been higher, a prediction that is confirmed by the values obtained here.

An apparent contradiction is the following: this region has very high uplift rates, but the relief of the Andes is very low (<2,500 m) compared with northern portions of the chain. This almost certainly implies a very fast erosion rate, which is in agreement with the present conditions of the area and with the heavy Pleistocene glaciations which developed here. Sediment accumulation in the nearby oceanic trench is thus, a result of high uplift rates and high erosion rates in the adjoining Andes.

ACKNOWLEDGEMENTS

This research has been supported by FONDECYT Grants 056 and 1181 to FH and Grant under the Mombusho International Scientific Research (Project N° 01041040) to YO. ^{14}C analyses were performed at Gakushuin University. Field assistance by J. Cembrano, C. Maureira (Departamento de Geología, Universidad de Chile) and F., D. and A.B. Hervé is acknowledged. Professor M. Beck (Western Washington Univer-sity) enthusiastically provided the calculations about glacioisostatic rebound. Revisions by M. Beck, J. Varela (Departamento de Geología, Universidad de Chile); R. Paskoff (University of Lyon) and S. Barrientos (Departamento de Geofísica, Universidad de Chile) greatly improved the text. This paper was finished during a stay of FH at the Laboratoire de Pétrologie, Université d'Aix-Marseille III on an EEC scholarship. Diego Morata's help with the computers at Marseille is acknowledged.

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Manuscript received: April 14, 1992; accepted: October 9, 1992.