NOTA GEOLOGICA

GEOCHRONOLOGY OF MARINE TERRACES AT CALETA MICHILLA, NORTHERN CHILE; IMPLICATIONS FOR LATE PLEISTOCENE AND HOLOCENE UPLIFT

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RESUMEN

Dataciones de conchas de moluscos, provenientes de los depósitos de terrazas marinas, mediante radiocarbono y aminoestratigrafía, han proporcionado antecedentes de un levantamiento tectónico durante el Pleistoceno tardío y Holoceno, en Caleta Michilla, en la costa de Chile, al norte de Antofagasta. El levantamiento activo tuvo lugar a lo largo de esta sección de la costa durante el Holoceno, con un mínimo de 3-4 m de levantamiento tectónico desde la formación de la terraza inferior, *ca.* 6.725 +/- 95 años radiocarbono antes del Presente. Por lo menos 33 m de levantamiento tuvieron lugar desde la formación de la siguiente terraza más alta, la cual ha sido datada aminoestratigráficamente como perteneciente a la última edad de glaciación (80.000 a 125.000 años).

Palabras claves:Terrazas marinas, Levantamiento terciario; Razones de levantamiento, Holoceno, Caleta Michilla, Chile

INTRODUCTION

Much of the northern and north-central Chilean coastline is backed by one or more marine terraces, in places extending to more than 100 m above modern sea level. The available dates on major terraces are all of Pleistocene age (Radtke, 1987a, b,1989; Hsu *et al.* 1989). Recent work dating Pleistocene terrace deposits along the coast indicates that the elevation of the terraces above modern sea level is a result of long-term, relatively slow, tectonic uplift of the continental margin (Radtke, 1987 a, b, 1989; Hsu *et al.*, 1989; Leonard and Wehmiller, in prep.). Deposits yielding Holocene dates have been found on the modern shore platform to elevations of 1 to 5 m above modern sea level (Paskoff, 1973). However, distinct Holocene terraces above the modern platform have not been reported, and the extent to which the relatively higher Holocene sea levels are a result of tectonism along coast rather than variations in eustatic sea level is not clear. Paskoff (1973) took the latter position, arguing that no evidence has been found which would indicate significant Holocene crustal movement along the northern Chilean coast. This paper reports on a Holocene marine terrace at Caleta Michilla on the northern coast. The terrace is separated from the modern shore platform by a 4 to 5 m scarp. The age of deposits on the terrace and its altitude above modern sea level indicate that several meters of tectonic uplift has taken place at the site during the Holocene.

STUDY SITE

Caleta Michilla is a small (approximately 1.5 km long) embayment along the Pacific coast of Chile, north Antofagasta, at a latitude of 22°43'S (Fig. 1). The modern shore platform at Caleta Michilla is backed by three marine terraces which we call the 'Low', 'Intermediate', and 'High' terraces in this paper (Figs. 1, 2). Shoreline features around the bay were surveyed form the mean high-tide line by hand levelling and barometric altimetry. Surveyed paleoshoreline altitudes on the modern platform and the low terrace are probably accurate within a meter. Altitudes on the higher terraces are probably accu-

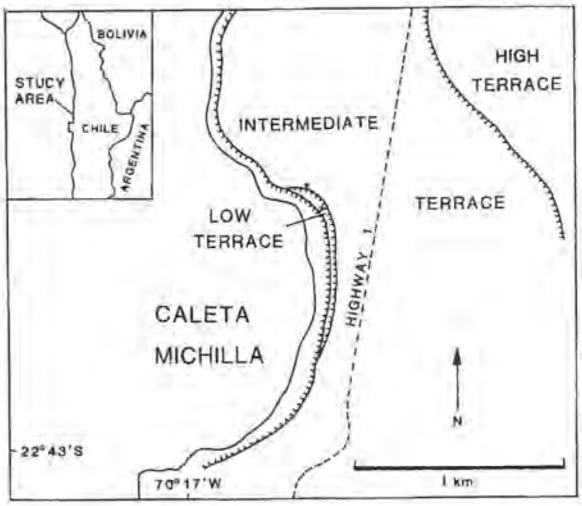

FIG. 1. Study area map of Caleta Michilla. Hachure lines indicate marine terrace scarps. Stars indicate samples sites on the Low and Intermadiate terraces.

rate to within 2-3 m. The modern platform, which is approximately 150 m wide, reaches an altitude of only 1-2 m above modern mean sea level. The low terrace, the least developed of the four shoreline features, is only about 15 m wide at its maximum width and is not continuous around the embayment. The landward edge, or 'shoreline angle' of the terrace has an altitude of 6-7 m. Above the Low terrace are two much better developed and more continuous terraces. The Intermediate terrace, nearly 1 km wide, has a seaward edge altitude of about 21 m, and a shoreline angle at 39-40 m. The High terrace is moderately dissected and partially buried beneath alluvium and colluvium. Dissection of the seaward edge of the terrace and alluvial/colluvial cover of its landward portions made accurate altimetry impossible.

Each terrace is capped by fossiliferous marine sediments. Whole shells of several genera of marine mollusks were sampled from terrace sediments on the Low and Intermediate terraces (Fig. 1). Radiocarbon and amino acid dating of shells from these terraces provides a chronologic framework for the study of uplift at the site.

DATING OF THE TERRACES

METHODS

Dating of the Low and Intermediate terraces at Caleta Michilla was accomplished using radiocarbon and amino acid geochronologic techniques on mollusk shells from terrace deposits. Shells of Holocene age are most accurately dated by radiocarbon methods. Accurate radiocarbon dating is limited to shells less than about 30,000 years old, and as a result, other dating methods must be used for dating all but the very youngest Pleistocene deposits. Absence of coral from the deposits at Michilla precluded accurate Th/U dating. The utility of amino acid analysis in providing both relative and numerical dates for Pleistocene marine deposits in northern Chile and Southern Perú has been shown in recent studies (Hsu, 1988; Hsu *et al.*, 1989; Leonard and Wehmiller, in prep.), and the technique was utilized in this study.

The principles of amino acid geochronology and its application to Chilean and Peruvian marine mollusks are discussed in detail in Hsu *et al.* (1989) and the reader is referred to that paper for a full discussion of our field and lab techniques. Use of mollusk shell amino acids for dating is based on the post-mortem diagenesis of amino acids in shell protein from levo or 'L' isomers to dextro or 'D' isomers, a process known as 'racemization'. The ratio between D and L isomers increases progressively from 0 at the time of death to an equilibrium value between 1.0 and 1.3. Use of amino acid ratios to determine numerical ages, although possible, is difficult because racemization occurs at a decreasing rate with time, and because racemization rates are temperature dependent. Their use for relative dating and correlation in a limited geographical area is simpler and can be undertaken with considerable confidence.

In this study we measured D-alloisoleucine to L-isoleucine ratios (hereafter called A/I values) in shells of genera *Protothaca* and *Mulinia* from terrace deposits. Work elsewhere along the Chilean and Peruvian coasts indicates that A/I values from these genera provide generally consistent and reliable chronologic data (Hsu; 1988; Hsu *et al.*, 1989; Leonard and Wehmiller, in prep.). Racemization rates differ slightly between the genera, but it is possible to make an approximate conversion between them (Hsu, 1988).

TABLE 1. AMINO ACID RATIOS AND RADIOCARBON DATES ON MOLLUSK SHELLS FROM MARINE TERRACES AT CALETA MICHILLA AND PUNTA TAMES, CHILE

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

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

DATING OF THE LOW TERRACE

A single *Mulinia* shell sampled from marine sediments 1 m below the surface of the Low terrace (Fig. 2) yielded a Holocene radiocarbon date of 6725+/-95 BP (GX-15475). As a check on this date, we measured A/I values in this and two other *Mulinia* shells recovered at the same depth (Table 1a). The three shells yielded a mean A/I value of 0.16+/-0.03. As will be discussed below, this value is substantially lower than A/I values found on shells on terraces believed to be of last interglacial age (*ca.* 80,000-125,000 years) in the Michilla area, and is consistent with the Holocene radiocarbon date.

DATING OF THE INTERMEDIATE TERRACE

Shells of several mollusk genera were recovered from marine sediments on the Intermediate terrace at Caleta Michilla (Fig. 2). A/I values were determined for three *Protothaca* shells recovered from a road cut approximately 3.5 m below the terrace surface (Table 1b). An additional three *Protothaca* shells were analyzed from sediments on what appears to be a continuation of the same terrace south of Punta Tames, approximately 4 km north of Caleta Michilla sample site (Table 1c). The A/I values of five of the six shells (two from Michilla and all three from Tames) cluster closely around 0.4. In an earlier paper (Hsu *et al.*, 1989) we referred to cluster of A/I values averaging 0.403 +/-0.024 (n=9) at these two sites, and on the 38 m terrace at Caleta Hornos 10-12 km further south, as northern Chile aminozone A. Based on electron spin resonance dating of two shells from the terrace deposits at Caleta Hornos and a number of

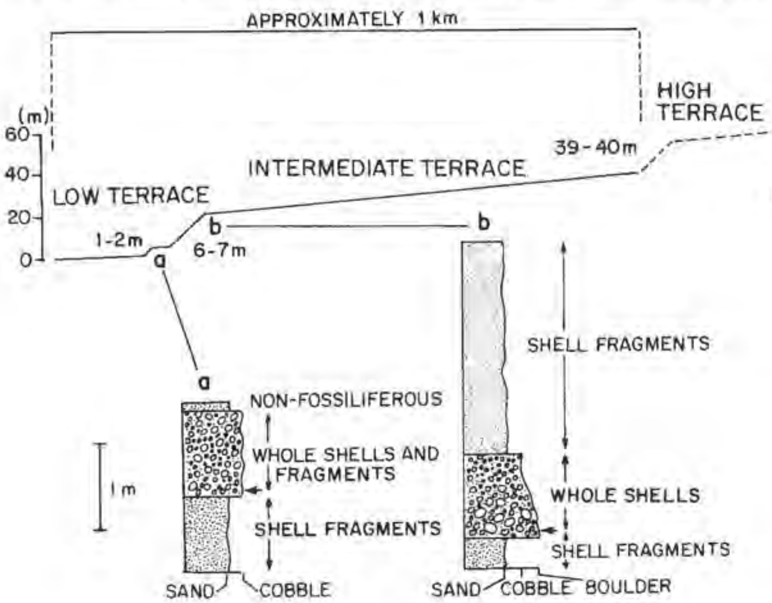

FIG. 2. **Top.** Schematic cross section of terraces at the northern end of Caleta Michilla. Profile of High terrace is dashed because erosion and alluvial/colluvial cover obscure original terrace morphology. **Bottom.** Stratigraphy of upper 2-4 m of terrace sediments at sample sites on the Low (a), and Intermediate (b) terraces. Sample localities are indicated by heavy horizontal arrows.

other ESR and radiocarbon dates from southern Chile and northern Perú (Radtke, 1987a, b,1989), we argued in Hsu *et al.* (1989) that aminozone A shells date from the last interglacial transgression, probably from the maximum sea level stand *ca.* 125,000 years ago, but possibly from a younger high stand as recent as 80.000 years. Thus, we believe that the Intermediate terrace at Caleta Michilla was formed during the last interglaciation, between 80,000 and 125,000 years ago. The single shell at Michilla with a higher A/I value (0.56) appears to have been reworked from older deposits into the Intermediate terrace deposits, and in fact its ratio is very close to those found in shells from a higher terrace at Punta Tames.

Hsu's (1988) work in Perú suggests that racemization in *Mulinia* shells is slightly slower than in *Protothaca* shells and that to compare the *Mulinia* ratios from the Low terrace to *Protothaca* ratios on the Intermediate terrace, the former should be increased by approximatelly 20%. Even with this correction, it is clear that the Intermediate terrace shells show a much greater degree of racemization than those on the Low terrace. Because of the nonlinearity of the racemization reaction through time and its rate sensitivity to changing temperatures, it is difficult to estimate precisely how much of a time difference is represented by the different degrees of racemization. In a detailed study of Holocene and late Pleistocene amino acid racemization on marine terraces in New Guinea, Hearty and Aharon (1988) found that shells only 7,000 radiocarbon years old had A/I ratios 50 to 60% as high as those in shells dating from the last interglacial maximum sea level stand (dated at 127,000 in their paper), a result consistent with the amino acid ratios and our proposed terrace ages at Caleta Michilla.

LATE PLEISTOCENE AND HOLOCENE UPLIFT

In order to estimate the amount of uplift which has taken place since the formation of a marine terrace, and to evaluate uplift rates, the position of eustatic sea level at the time of terrace formation must be known. There is considerable controversy about the timing and magnitudes of the late Quaternary eustatic sea level variations. One of the few points of general (although not unanimous) agreement is that the last interglacial maximum eustatic sea level stand occurred between 130,000 and 120,000 years ago (125,000 being the most commonly cited age), and that at that time, eustatic sea level was approximately 6 m above present (Bloom and Yonekura, 1985). During later stages of the last interglaciation, between 120,000 and around 80,000 years ago, eustatic sea level fluctuated significantly, with two low stands, with sea level several 10's of meters below present sea level, and two high stands. Most workers believe that during the latter high stands sea level was 10 to 20 m below present sea level, but recently Vacher and Hearty (1989) have argued that during the final high stand, *ca.* 80,000 years ago, sea level rose to approximately its present position. Studies from throughout the Pacific Basin indicate that preserved marine terraces generally date from periods of high relative sea level stands (Bloom and Yonekura, 1985). The geochronology discussed above indicates that the Intermediate terrace at Caleta Michilla was formed sometime during the last interglacial, and thus its formation probably dates from either the *ca.* 125,000 year maximum sea level stand or from one of the two relatively high stands later in the interglacial. If, as we believe most likely, the terrace formed during the last interglacial sea level maximum, approximately 6 m of its present elevation above modern sea level must be due to global eustatic sea level fall, the remaining approximately 33-34 m must be due to uplift of the coast. This indicates a mean uplift rate of slightly less than 0.3 mm/year over the last 125.000 years. If, on the other hand, the intermediate terrace formed during one of the later high stands, when eustatic sea level was no higher than at present, at least 39-40 m of uplift must have taken place since the formation of the terrace, possibly as little as 80,000 years ago. This latter model would suggest a mean uplift rate higher than the 0.3 mm/yr discussed above, but a precise rate cannot be calculated without a clearer understanding of both the age of the terrace and eustatic sea level variations during the later stages of the last interglaciation.

A long standing controversy surrounds the nature of eustatic sea level changes during the Holocene. It has proven very difficult to develop a eustatic curve for the Holocene with a precision greater than a few meters because relative sea level changes at any given site reflect three factors -local tectonics, changing sea water volume (true eustasy), and isostatic adjustments of crust to changing sea level (hydro-isostasy). Modeling by Clark and his co-workers (Clark *et al.*, 1978; Clark and Lingle, 1979; Clark and Bloom, 1979) indicated that hydro-isostatic effects vary significantly from place to place, so that even in areas of tectonic quiescence, Holocene relative sea level curves may differ from one another by several meters. Based on these models, Clark and Bloom (1979) suggested that hydro-isostatic effects alone would have led to an approximately 1 m drop in relative sea level since about 5,000 years BP along the coast of Chile. Studies on tectonically stable coastlines in the southern hemisphere, which according to Clark *et al.* (1978) and Clark and Lingle (1979) should have experienced hydro-isostatic histories similar to that of the Chilean coast, indicate relative sea evel drops (including both hydro-isostatic and true eustatic components) of between 1 and 5 m since mid-Holocene time (Isla, 1989). At all but two sites the drop was 3 m or less, and at those two sites, in Brazil, the models of Clark and his co-workers predicted hydro-isostatic effects somewhat larger than those predicted for coastal Chile. It seems probable then that any mid-Holocene to present sea level drop in northern Chile, including both eustatic and hydro-isostatic components, was no more than 3 m.

Assuming a maximum 3 m drop in relative sea level since mid-Holocene time, a minimum of 3-4 m of tectonic uplift must have occurred since the deposition of marine sediment on the Low terrace at Caleta Michilla between 6,500 and 7,000 radiocarbon years ago. This is very likely an underestimation of the total amount of uplift, since the sediments were deposited during an interval when relative sea level was below its mid-Holocene maximum stand at nearly all Southern Hemisphere sites (Isla, 1989). The minimum mean uplift rate since the formation of the terrace then is approximately 0.5 m/1,000 years. In the light of the relatively small total amount of uplift which has occurred since the formation of the Low terrace, however, it is not unlikely that a single seismic event, or a very few events, may be responsible for the Holocene uplift, and so it may not be realistic to view this as a long term mean uplift rate.

CONCLUSIONS

The Holocene age of the Low terrace at Caleta Michilla provides evidence that several meters of uplift has occurred along the coast during the last 10,000 years, as the present altitude of the terrace cannot be explained by eustatic and hydro-isostatic effects alone. The terrace thus provides the first clear evidence of Holocene tectonism along the northern Chilean coast analogous to that which has been reported by other workers in south-central Chile (Kaizuka *et al.*, 1973). The altitude and age of the terrace suggest that uplift since 7,000 years BP has averaged at least 0.5 mm/yr, a rate of approximately the same order as longer term uplift rate deduced from the age and altitude of the Intermediate terrace at Michilla. However, the episodic nature of uplift and the possible long recurrence interval of large tectonic events along the northern coast suggests caution in using Holocene data to evaluate mean uplift rates.

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