Plio-Quaternary marine terraces and their deformation along the Altos de Talinay, North-Central Chile

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ABSTRACT

Plio-Quaternary faulted marine terraces are distinctively recognizable at four levels along the 110 km-long coast around the Altos de Talinay, north-central Chile.The authors named them the Talinay I, II, III and IV terraces in descending order. The Talinay I terrace reaches 675 m in altitude with a 6-8 km wide terrace surface which probably emerged in the Pliocene-early Pleistocene time. The Talinay III terrace (30-50 m) and Talinay IV terrace (20-30 m) are tentatively assigned to the oxygen isotope stage 9 and 5e, respectively. Height distribution of the paleoshorelines shows that the uplift pattern varied from a rapid updoming in the early Pleistocene to a regional uplift after the middle Pleistocene. Most faults trend nearly north-south and are dip-slip normal faults, which show progressive deformation of the Talinay terraces I and II. No fault activity is seen on younger Talinay III and IV terraces. Such fault movements, chronologically synchronized with the early Pleistocene updoming of the Altos de Talinay, suggest that the extensional stress field was predominant in the upper crust. The change in tectonic pattern, probably, resulted from the weakening of coupling between the Nazca Plate and South America Plate in the middle Pleistocene.

Key words: Chile, Altos de Talinay, Marine terraces, Quaternary faults, Uplift rate, Deformation pattern, Quaternary tectonics.

RESUMEN

Deformación de terrazas marinas plio-cuaternarias en la región de los Altos de Talinay, centro-norte de Chile. Terrazas marinas falladas, de edad plio-cuaternaria forman cuatro niveles escalonados a lo largo de 110 km de costa que bordean los Altos de Talinay, en el centro-norte de Chile. Estas terrazas reciben el nombre de Talinay I, II, III, y IV, en un orden de altura decreciente. La terraza I, que alcanza una altura de 675 m sobre el nivel del mar y un ancho de 6-7 km, probablemente, empezó a solevantarse a fines del Plioceno o a comienzos del Pleistoceno. En la cronología isotópica del Cuaternario, la terraza Talinay III (30-50 m) y la terraza Talinay IV (20-30 m) son tentativamente asignadas a los estadios 9 y 5e de isótopos de oxígeno, respectivamente. La distribución altimétrica de las antiguas líneas de costa indica un rápido abovedamiento a principios del Pleistoceno, seguido por un solevantamiento regional después del Pleistoceno medio. La mayoría de las fallas, de orientación norte-sur, son fallas normales que revelan una deformación progresiva de las terrazas Talinay I y II. No hay fallas visibles en las terrazas III y IV. Los movimientos de falla relacionados con el abovedamiento de los Altos de Talinay, ocurrido a comienzos del Pleistoceno, indican un régimen tectónico distensivo en la parte superior de la corteza. Este cambio en la tendencia tectónica, probablemente, fue el resultado de una disminución del acoplamiento entre la Placa de Nazca y la Placa Sudamericana en el Pleistoceno medio.

Palabras claves: Chile, Altos de Talinay, Terrazas marinas, Fallas cuaternarias, Velocidad de solevantamiento, Tipo de deformación, Tectónica cuaternaria.

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INTRODUCTION

PRESENT STUDY AND REGIONAL SETTING OF THE STUDY AREA

This paper describes marine terraces and faults around the Altos de Talinay and their southern extension in north-central Chile, and discusses coastal evolution and Quaternary tectonic movements based on their features. The study area is about 110 km long, located between *ca.* 30°15' and 31°10'S (Fig. 1). The coastline is nearly parallel to the Peru-ChileTrench, about 70-100 km west of the coast and 7,000-8,000 m deep, that marks the contact between the oceanic Nazca Plate and the continental Southamerican Plate. The Nazca Plate is subducting below the South-american Plate associated with the Chile megathrust (Hervé and Thie e, 1987). Rate of convergence is 9.3 mm/yr with a direction of east to northeast (Minster and Jordan, 1978; Corvalán *et al.*, 1981). Seismicity is active along the coastal scarp, 1,000 m deep below the continental slope to the Andes. For example, the 1966 Taltal earthquake (M=7,75) occurred in northern Chile with sinistral slip component. Surface shear zones en echelon associated with this earthquake are regarded to represent the underground faulting (Lemke *et al.*, 1968).

The Altos de Talinay extend with a north-south orientation northward of the mouth of Río Limarí, and comes to an end at Punta Lengua de Vaca, west of Bahía Tongoy. South of Río Limarí, which crosses them through a deep gorge, the Altos de Talinay run SSE and reach their maximum height of 762 m a.s.l. at Cerro Talinay (Fig. 1), the Altos de Talinay are formed, mainly, of Paleozoic rocks intruded by Jurassic granitoids (Thomas, 1967; Godoy, 1976; Gana, 1991; Rivano and Sepúlveda, 1991). The Altos de Talinay form a major structural and geomorphic uplifted unit (Fig. 2), separated by the north-south trending Puerto Aldea Fault from a graben filled up by continental gravels, brought in by an ancestor of Río Limarí, which interfingers northward with the fossiliferous soft marine sandstone of the Coquimbo Formation, ascribed to the middle to upper Miocene (Martínez, 1979). During Plio-Quaternary times a flight of step-like marine platforms up to *ca.* 200 m in elevation were cut into these sandstones, south of Bahía Tongoy. The highest terrace, considered as Pliocene in age (Paskoff, 1993) merges with the highest fluvial terrace of Río Limarí. The Altos de Talinay correspond to rocky

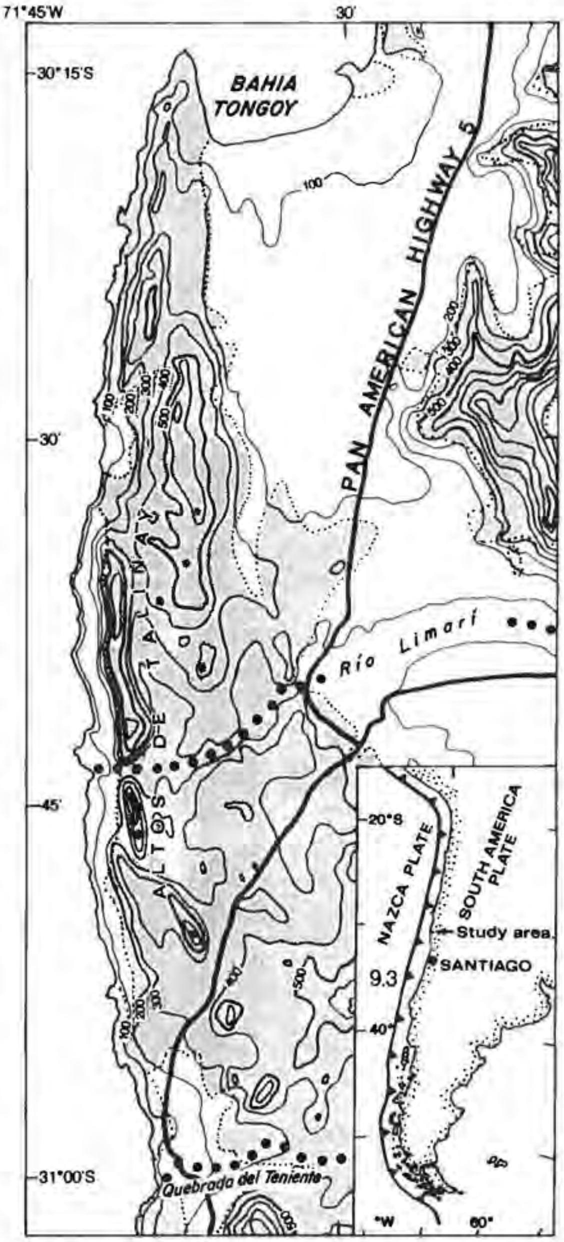

FIG. 1. Map showing the location and regional setting of the study area. Contours represent general topography with 100 m interval. Shaded area indicates the areas underlain by pre-Tertiary rocks (after Geologic map of Chile, 1:1.000.000, 1982). Inset shows the tectonic setting of the study area (after Corvalán et *al.*, 1981).

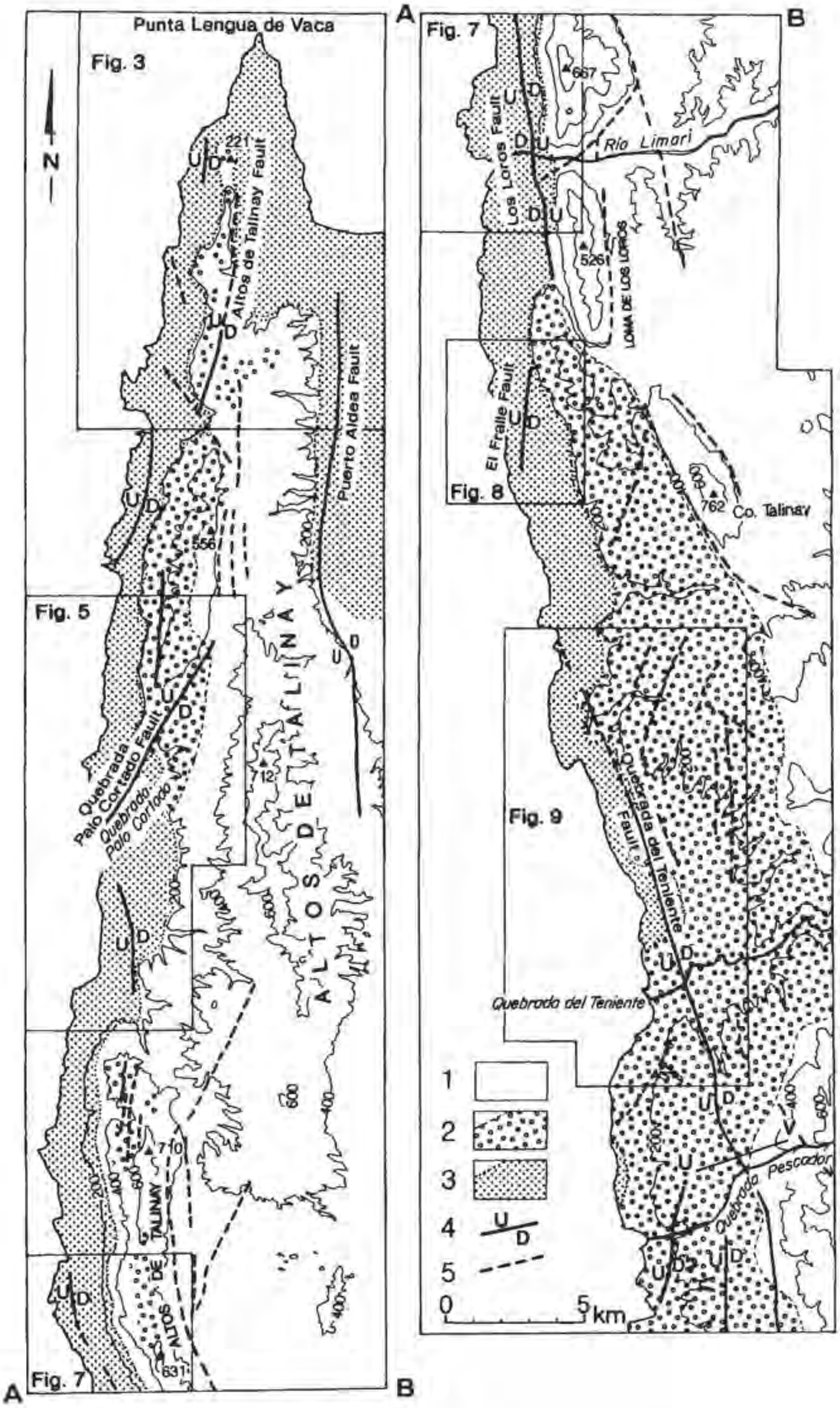

FIG. 2. Map showing distribution of marine terraces and faults. Contours (200 m interval) are from topographic maps at a scale of 1:50,000. Rectangles indicate the areas of detailed maps. 1- mountains and hills; 2- Talinay I shoreline and area covered by Talinay I terrace; 3- Talinay II shoreline and area covered by Talinay II, III and IV terraces; 4- Quaternary fault with indication of upthrown (U) and downthrown (D) blocks; 5- prominent lineament.

wave-cut terraces which have been strongly deformed by recent crustal movements. Evidence for such marine origin is suggested by their leveled forms frequently covered by thin patches of beach deposits.

The Altos de Talinay contrast with the surroundings of Bahía Coquimbo situated just northward (30°S), which, on the contrary, have been evenly and slowly uplifted during the Plio-Quaternary, since the highest marine terrace of the area only reaches about 120 m above present sea level (Paskoff, 1970). Southward of the Altos de Talinay, effects of recent crustal movements rapidly decreases and from the Río Choapa mouth (31°30'S) only moderately uplifted rocky wave-cut platforms are found down to the Río Aconcagua (30°S). Therefore, the coastal belt of north-central Chile appears to be divided into independent segments, each one characterized by a different tectonic trend. Such a division probably reflects discontinuities and different behaviors in the underlying subduction zone (Paskoff, 1977).

Material for this paper was obtained during a field work in September to November, 1989. Large scale (*ca.* 1: 20,000) air photographs were used for the preparation of the maps of marine terraces and faults.

PREVIOUS STUDIES

A preliminary report on the terraces and tectonic movements between the mouth of Río Limarí and Quebrada del Teniente was published by Paskoff (1966). Chávez (1967) described marine terraces around the Altos de Talinay based on air photographs interpretation and emphasized the evidence of Quaternary tectonic movements, which strongly uplifted and tilted the marine terraces of this area. Post-Pliocene vertical movements on the Puerto Aldea Fault was discussed by Thomas (1967) and for the Quebrada del Teniente Fault by Rivano and Sepúlveda (1991), who also suggested a left-lateral strike-slip along the Quebrada del Teniente Fault.

Paskoff (1970) gave a detailed account of the geomorphology and Plio-Pleistocene evolution of the Altos de Talinay, showing the distribution of faulted marine terraces on a 1:250,000 scale colour map. The complicated history of the lower course of Río Limarí is related to the geomorphic evolution of the Altos de Talinay. The Río Limarí which once flowed towards Bahía Tongoy and then changed its outlet, now running directly westward to the Pacific Ocean through a deep gorge cut across the Altos de Talinay. Paskoff (1970) recognized two stages in the tectonic history of the Altos de Talinay: **1-** uplift at the end of the Pliocene, and **2-** tilting and faulting of the marine terraces during the Quaternary, mainly by activity of the Puerto Aldea Fault and Quebrada del Teniente Fault as well as other less important faults.

No detailed maps showing the distribution of marine terraces and faults were included in the mentioned articles and no discussion about the uplift rate of marine terraces, and slip rate of faults and their possible present activity is available. This information is vital to understand the tectonic history of this area, which is adjacent to the significant convergent plate boundary at the Peru-Chile trench.

MARINE TERRACES AND FAULTS

CLASSIFICATION AND GENERAL NATURE OF MARINE TERRACES

A flight of marine terraces, up to more than 600 m a.s.l., are well preserved surrounding the Altos de Talinay. These terraces can be roughly divided into four main levels from Talinay I to IV in descending order, based on their geomorphologic features, such as continuity and degree of dissection of terrace surfaces, and height of former shorelines. The approximate position of the former shorelines of Talinay I and II terraces is shown in figure 2. Most of the marine terraces are abrasion platforms, which are covered by thin and discontinuous beach deposits.

- **Talinay I terrace** is the highest group of the terraces, ranging from an altitude of *ca.* 200 m a.s.l.

in the north of the study area, to 675 m in the central part, and *ca.* 400 m a.s.l. in the south. This terrace forms narrow and flat summits in the northernmost part of the Altos de Talinay and locally on the southern part. It forms, however, an increasingly wider terrace at the western foot of the Altos de Talinay, becoming wider southwards and reaching up to 6-8 km in width. Talinay I is a well defined terrace, but dissected with a slightly rolling undulatory surface, and it can be locally subdivided into two or three levels, separated by low terrace risers.

- **Talinay II terrace** is separated by a distinctive terrace riser from Talinay I and is the best defined continuous terrace in the study area. The height of the Talinay II shoreline ranges from *ca.* 100-140 m a.s.l. The terrace reaches a width of 3 km along the Bahía Tongoy coast, but it is usually 1-2 km in width, becoming very narrow near the Quebrada del Teniente Fault, where it is less than 0.5 km wide.
- **Talinay III terrace** is very narrow and only locally preserved in the northern and southern parts of the study area, and ranges in height from 35 m to 50 m a.s.l.
- **Talinay IV terrace**, up to 1 km in width, is commonly separated by a neat and steep terrace riser from the Talinay II terrace. Only locally, a terrace riser separates it from the Talinay III terrace. Talinay IV terrace continuously fringes the present coastline, but disappears in the south of the study area. Its width reaches 1 km and its height is about 20-30 m a.s. l.

AGE OF THE TERRACE LEVELS

Terrace deposits in the study area generally do not contain shells, except for several ^{14}C dated Holocene shells (Ota and Paskoff, 1993), and some shell samples collected from the Talinay IV terrace deposits near Bahía Tongoy that have been submitted for ESR dating (Koba *et al.*, in prep.). Therefore, direct age determination of marine terraces in this area is not possible at this stage.

Based on the continuity of the terraces surrounding the Altos de Talinay with dated terraces of the Bahía Herradura, situated northward (29°59'S), it is possible to make some age estimation. The Talinay III and IV terraces form continuous levels with the Herradura I and II terraces, respectively, in the northern areas of Bahía Coquimbo and Bahía Herradura (Paskoff, 1970). Radtke (1989) considered that the Herradura I terrace was older than the last interglacial maximum stage (oxygen isotope stage 5e), based on amino acid, ESR and U-series dating of shells. Based on information supplied by Leonard and Wehmiller (1992), Paskoff (1991) suggested that the Herradura I and II terraces correspond to oxygen isotope stage 9 and 5e, respectively. Following this estimation, the Talinay IV terrace, a continuous level with the Herradura II terrace, can be assigned to isotope stage 5e, and the Talinay III terrace to stage 9. If so, then the much higher Talinay II and I terraces must be assigned, at least, to middle Pleistocene age (*ca.* 300 ka ago), or most probably, to some older time.

FAULTS

The Altos de Talinay and the marine terraces surrounding them are cut by many north-south or NNW-SSW oriented faults, roughly parallel to the trend of the Altos de Talinay (Fig. 2; *e.g.*, the Puerto Aldea Fault, the Altos de Talinay Fault and its southward extension, and the Quebrada del Teniente Fault). However, most of the observed faults are concentrated on the west side of the Altos de Talinay. Except for the Quebrada del Teniente and Puerto Aldea Faults, which correspond to major tectonic features (Paskoff, 1970), most of the faults could be traced only for a short distance.

DESCRIPTION OF MARINE TERRACES AND FAULTS

Five areas, shown in figure 2, were selected for a more detailed description of the terrace morphology and associated deposits, and the description of the faults that offset them.

Northernmost part of the Altos de Talinay and south of Bahía Tongoy (Figs. 3 and 4). The Talinay I terrace is preserved as a narrow rounded summit of the Altos de Talinay, with a variable surface height ranging from *ca.* 220 m a.s.l. in the north to 370 m a.s.l. in the south. The Talinay II terrace, separated from Talinay I by a terrace riser of about 70-80 m high, is the most continuously preserved terrace, with a former shoreline height of *ca.* 100-140 m a.s.l., becoming higher southwards. This terrace is especially wide on the eastern side of the Altos de Talinay, up to *ca.* 2.5 km, and continues to the very extensive terrace along

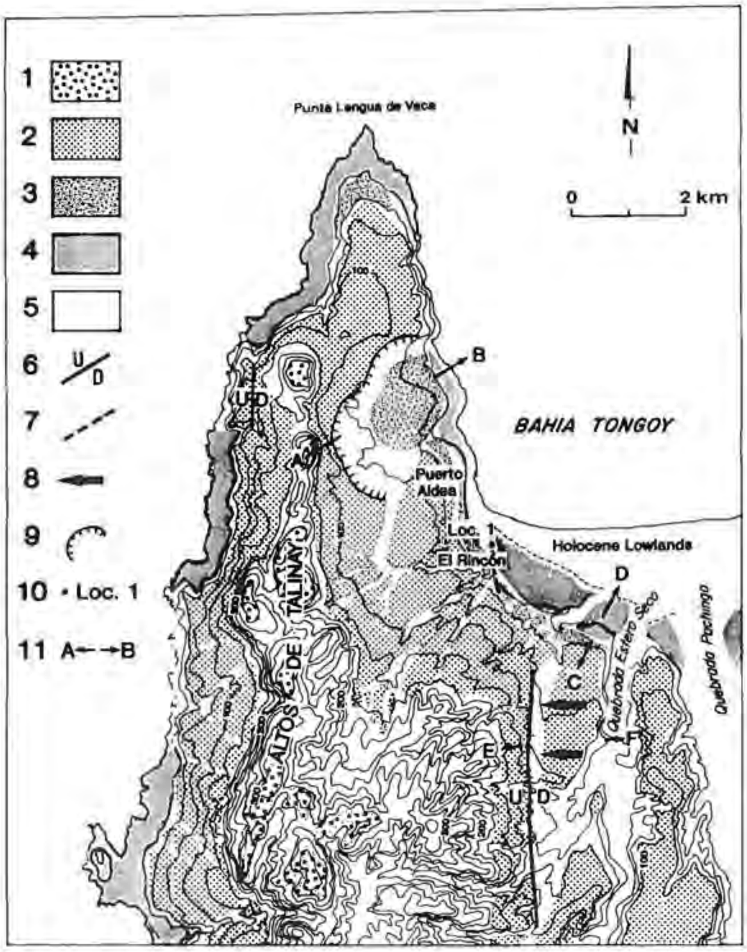

FIG. 3. Geomorphologic map of the northernmost part of the Altos de Talinay. Contours (25 m interval) are from 1:50,000 topographic map. 1- Talinay I terrace; 2- Talinay II terrace; 3- Talinay III terrace; 4- Talinay IV terrace; 5- Slope; 6- Quaternary fault; 7- lineament; 8- tilt of the terrace; 9- slump scarp; 10- location described in the text; 11- location of profiles. The same symbols are commonly used in figures. 5, 7, 8 and 9.

Bahía Tongoy. In contrast, the Talinay III terrace, about 45 m a.s.l., is limited to the eastern and northernmost part (Punta Lengua de Vaca), and generally is narrow, but well developed on the west of Bahía Tongoy. The Talinay IV terrace, 20-30 m a.s.l. is narrow, and fringes continuously the present coastline. On the south of Bahía Tongoy, this terrace is rather wide and is fringed by a Holocene lowland with a series of beach ridges. ^{14}C dates and progradation rates of these deposits are discussed in a separate paper (Ota and Paskoff, 1993).

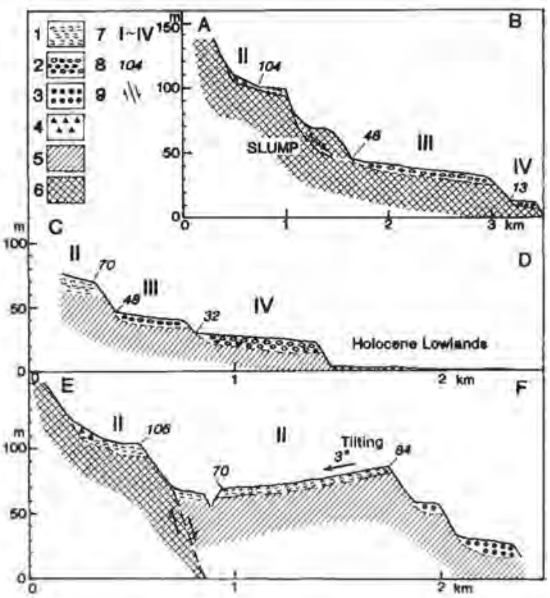

FIG. 4. Topographic profiles of terraces with some geological information. Locations are shown in figure 3. 1- 'losa'; 2- beach gravels; 3- fluvial gravels; 4- slope-wash deposit; 5- Miocene sandstone; 6- pre-Tertiary rocks. The same symbols are used for profiles of figures 6 and 8.

No deposits exist on the Talinay I terrace level. The Talinay II terrace in the western area is covered by a beach gravel veneer. On the west and south of Bahía Tongoy, the Talinay II terrace is underlain by a well identified '**losa**' (hard layer of beach gravels with abundant shells cemented by calcareous material) (Profiles C-D and E-F of Fig. 4). Such a '**losa**' is not found on the Talinay III and IV terraces.

Two interesting examples of marine terrace deformation are found in the area shown in figure 3. One is an arcuate slump scar at the back of Talinay III terrace, on the west of Bahía Tongoy (Profile A-B of Fig. 4). This slumping occurred after the emergence of Talinay II terrace, and probably, prior to the emergence of Talinay III terrace. However, the abnormally low altitude of Talinay IV terrace (only 13 m a.s.l.) may suggest that the slumping occurred after the formation of Talinay IV.

The second example corresponds to the westward tilting and faulting of Talinay II terrace on the south of Bahía Tongoy. The eastern rim of this terrace has an altitude of 84 m a.s.l. and the western limit is 70 m a.s.l. (Profile E-F, Fig. 4). This terrace continues to a small terrace on the west across a 'quebrada'. Farther west, the same terrace that is underlain by a '**losa**' resting on the abrasion platform of Paleozoic rocks, is 105 m a.s.l. A scarp about 30 m high within Talinay II continues to an exposure of the Puerto Aldea Fault at Location 1, near El Rincón and is probably a fault scarp. Tilting of the Talinay II terrace might be associated with activity on this fault. An excellent section (Paskoff, 1970) is exposed along a 'quebrada' west of El Rincón (Loc. 1). On both banks of the 'quebrada', Miocene sandstones strike N20°-30°W with a westerly dip of 25-30°, and are unconformably overlain by 4 m thick beach deposits of Talinay IV terrace. About 100 m upstream, a fault shattered zone about 8 m wide within the Paleozoic rocks, strikes nearly north-south. Beach gravels of Talinay IV terrace also rest on the Paleozoic rocks as well as on the shattered zone. However, there is no fault within the Talinay IV deposits and no height difference of the Talinay IV terrace across this fault. This implies that the Puerto Aldea Fault was active after the formation of Talinay II, but has had no movement, at least, since the last interglacial maximum. The valley floor of this 'quebrada' and its tributary show an interrupted profile in which the valley floor on the Paleozoic rocks is several meters higher than that on the Miocene sandstones. This demonstrates that headward erosion is significantly controlled by differential erosion of the rocks on both sides of the fault, but does not necessarily represent a fault offset of the 'quebrada' gradient.

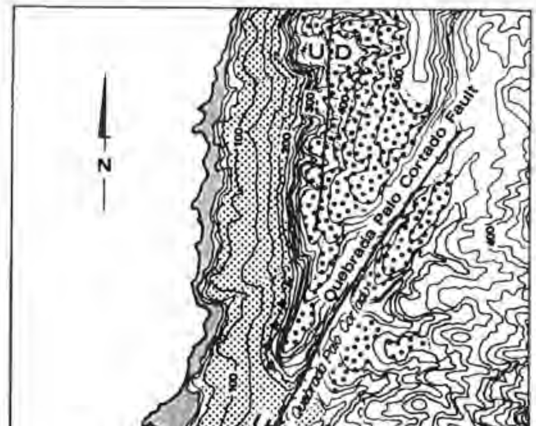

FIG. 5. Geomorphological map of the Quebrada Palo Cortado area. Symbols are shown in figure 3.

Quebrada Palo Cortado area (Figs. 5 and 6). Talinay I, II and IV terraces are continuously distributed along the coast. Talinay I, up to *ca.* 500 m a.s.l. in surface height, can be subdivided into two levels. Talinay II is separated from Talinay I by a very straight and sharp terrace riser *ca.* 160 m in height. An apparent inner margin of Talinay II is *ca.* 140 m a.s.l. However, the exact height of the former shoreline cannot be determined due to a thick cover of secondary slope-wash deposits that bury the shoreline angle.

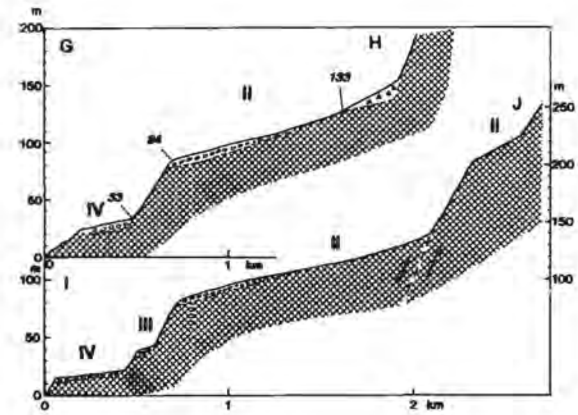

FIG. 6. Topographic profiles of terraces for Quebrada Palo Cortado area and Río Limarí area. Locations are shown in figures 5 and 7.

A distinctive straight fault running NNE-SSW is followed by Quebrada Palo Cortado and identified as the Quebrada Palo Cortado Fault (Paskoff, 1970). The terrace heights across the fault are significantly different: those for Talinay I and II on the upthrown side are *ca.* 460 m and 152 m a.s.l., and those for downthrown side are *ca.* 400 m and 141 m a.s.l., respectively, indicating a progressive relative uplift on the northwestern block since the formation of Talinay I terrace to some time after the emergence of Talinay II terrace. However, no height difference exists on Talinay IV, implying that this fault has been inactive, at least, since the last interglacial maximum.

Río Limarí area (Figs. 6, 7). On the northern and southern sides of the Río Limarí, the wide Talinay II terrace is well preserved and has a shoreline height of *ca.* 140-160 m a.s.l. It extends below a rather dissected Talinay I terrace, represented as the summit of the Altos de Talinay. A nearly north-south trending fault (Los Loros Fault; Paskoff, 1970) dislocates Talinay II terrace over a distance of about 8 km. The southern part of the Los Loros Fault appears as a west-facing fault scarp about 50 m high, resulting in an abnormal dissection of Talinay II on the upthrown side, where the former shoreline elevation is exceptionally high, up to *ca.* 200 m a.s.l. Northward, this fault changes its sense to produce an east-facing (range-facing) fault scarp, which has a smaller amount of displacement (*ca.* 10 m), and gradually the vertical displacement disappears northwards. South of figure 7, the Los Loros Fault continues southward as a straight line-

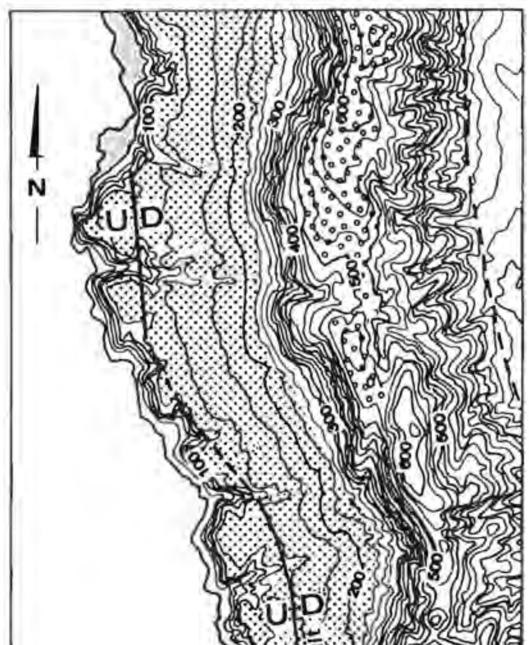

FIG. 7. Geomorphological map of the Río Limarí area. Symbols are shown in Figure 3.

ament striking SSE. However, surface displacement is not identified there. It is impossible to identify a fault activity on Talinay IV terrace, because the trace of the Los Loros Fault is entirely on the Talinay II terrace.

In the area shown in figure 7, two other faults are identified. One strikes north-south and limits the eastern margin of the Altos de Talinay. The other is a

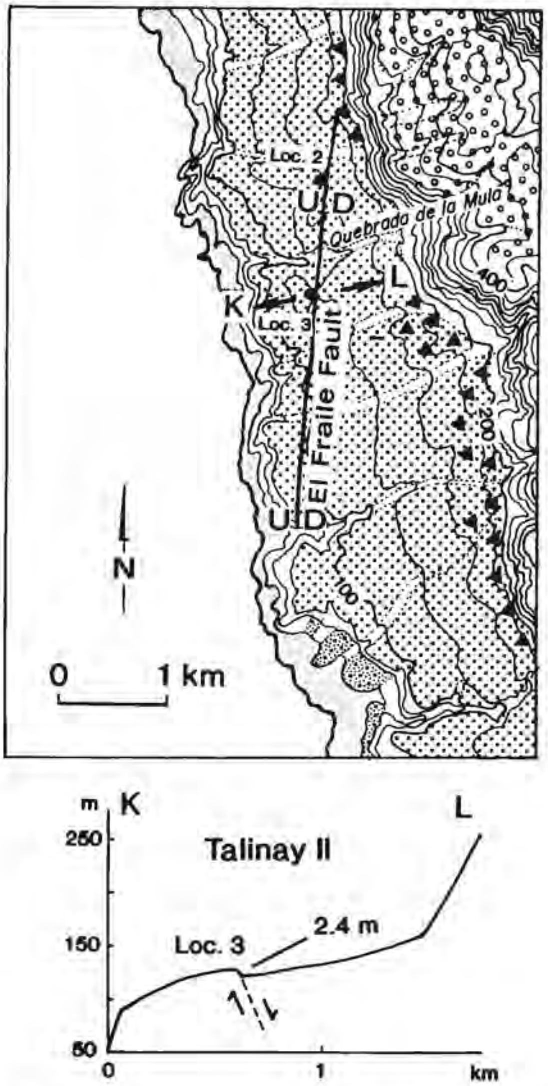

FIG. 8. Geomorphological map of the Quebrada de la Mula area and a topographic profile. Symbols as in figure 3.

NNW-SSW trending lineament north of Rio Limarí. No surface displacement on the younger surface is found on either of these two faults, however.

Quebrada de la Mula Area (Fig. 8). Three terraces, Talinay I (400-500 m a.s.l., subdivided into, at least, two), Talinay II (130-160 m a.s.l.), and Talinay IV (about 30 m a.s.l.) are well defined along the coast. It is difficult to know the exact elevation of the former shoreline height of Talinay II, because its shoreline angle below the high terrace riser (up to *ca.* 160 m) is covered by thick alluvial fan and slope-wash deposits. All the mapped terraces are abrasion platforms with only a few thin beach deposits.

A north-south trending east-facing (range-facing) scarplet dislocating the Talinay II terrace is clearly identified. This is the El Fraile Fault (Paskoff, 1970) and is about 5 km long. The scarp height is 2.4 m at Location 3, where the surface deformation is expressed by an abnormal arrangement of 140 m contour line, and decreases north- and southward. No vertical displacement is seen at Location 2.

Quebrada del Teniente area (Figs. 9 and 10). The terrace distribution map of this area (Fig. 9) is different from that of other areas described above. Here, the Talinay I terrace, which is subdivided into two or three levels, is very extensive, while the lower terraces are

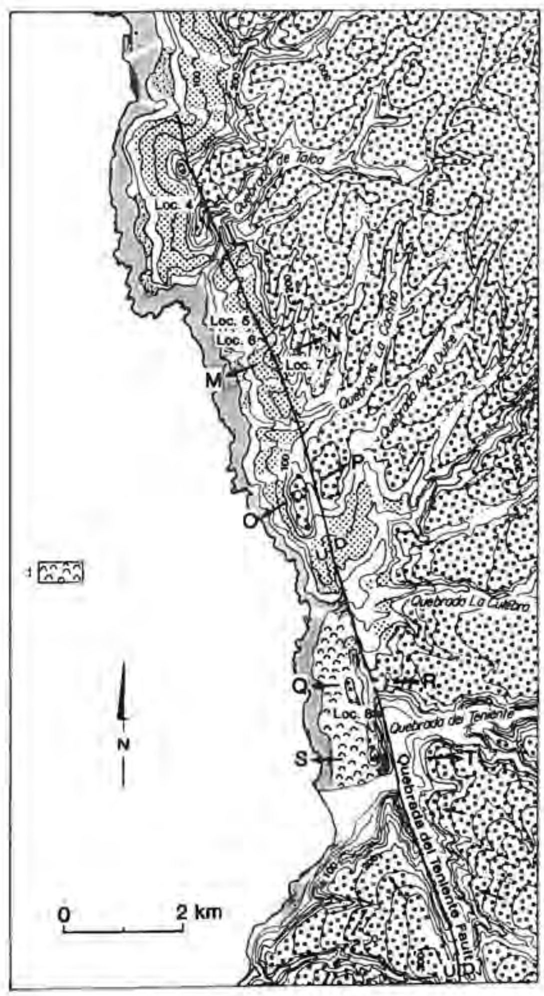

FIG. 9. Geomorphological map of the Quebrada del Teniente area. 1. sand dunes. Other symbols are shown in figure 3.

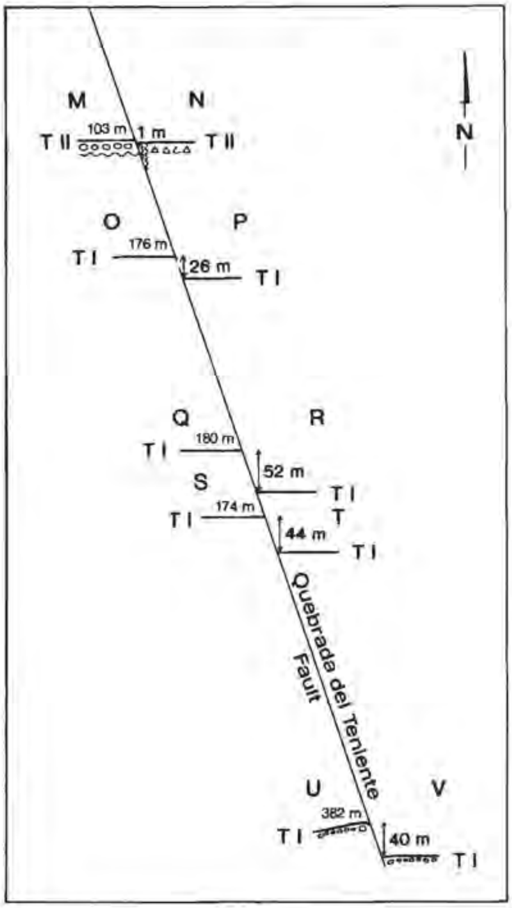

FIG. 10. Diagram showing vertical displacement of marine terraces in various transects along the Quebrada del Teniente Fault. Transect locations are shown in figure 9, except for U-V profile which is shown in figure 2.

rather narrow. North of the mouth of Quebrada del Teniente, sand dunes are developed on the marine terraces making the identification of terrace morphology difficult. Marine terraces in this area are usually characterized by thin beach deposits resting on abrasion platform of older rocks. The Talinay I terrace ranges in height from 350 m to 400 m a.s.l. The seaward gradient of the very wide Talinay I terrace south of Quebrada del Teniente becomes steeper toward the west, implying a possibility of westward downwarping of this terrace. The height of Talinay II is from 100 to 120 m a.s.l. Talinay III is at a height of *ca.* 40-50 m a.s.l. and IV is at about 20 m a.s.l.

The distinctively straight NNW-SSE trending Quebrada del Teniente Fault crosses this entire area, and it continues even farther southward, reaching *ca.* 25 km in total length. This fault is one of the most significant faults in the Talinay region (Paskoff, 1970). The Quebrada del Teniente Fault dislocates the Talinay I terrace over most of its trace, and locally, it also displaces the Talinay II terrace, forming an east-facing (range-facing) fault scarp (Fig. 10). The amount of vertical displacement on the Talinay I terrace is 40 m at Profile U-V, 44 m at Profile S-T, and reaches its maximum amount of 52 m at Profile Q-R. Displacement decreases northward to only 26 m at Profile O-P, and no displacement is observed at Location 4, although a straight lineament is still clearly traced. This fault dislocates Talinay II terrace northward. An east-facing scarplet, 1 m high is visible at Location 7 (Profile M-N), where beach deposits 1 m thick on the abrasion platform are exposed on the western upthrown side, and only slope-wash deposits are seen on the downthrown side, suggesting that the actual amount of dip-slip is more than 1 m. Fault exposures are seen at Locations 5 and 6. A shattered zone 10 m wide within Paleozoic metamorphic rock, with a fault plane striking N10° W, dipping 50° E, is exposed on the right wall of a small 'quebrada' at Location 6. The strike of this fault plane coincides with that of the Quebrada del Teniente Fault. A blue grey colored shattered zone, 8-10 m wide, is exposed at Location 5. This exposure of the shattered zone is well expressed by its color in a small quarry, although there is no surface displacement.

At Location 8 near the mouth of Quebrada del Teniente, left-lateral strike-slip of about 1 km has been reported (Paskoff, 1970), based on the offset of a scarp cutting the Talinay I terrace. This offset, however, seems to be only apparent, because: **1-** left-lateral offset cannot be seen anywhere else along this fault, **2-** upper Tertiary unconsolidated clastic deposits are exposed on the downthrown side of the fault, and **3-** some kilometers north of Quebrada del Teniente, a rather thick dyke which was dated 121.6 Ma crosses the fault without any horizontal displacement (Irwin *et al.*, 1988; García, 1991). Therefore, it is very likely that this apparent offset is actually caused by differential erosion between Miocene soft rocks on the downthrown side and Paleozoic resistant rocks on the upthrown side.

DISCUSSION OF UPLIFT AND FAULTING

UPLIFT PATTERN AND RATE

Height data of former shorelines as sea level indicators are summarized in figure 11. Talinay I terrace, which ranges from 220 m to 675 m a.s.l. indicates a considerable amount of differential uplift, with the highest uplift north of Río Limarí, and decreasing both northward and southward. This pattern is similar to that of the Altos de Talinay summit line. Judging from the possible westward downwarping of the very extensive Talinay I terrace in the southern area (Fig. 9), this uplift pattern may be an updoming with the long axis trending north-south and with, at least, westward downtilting. Another distinctive deformation is the vertical displacement of 150 m of the Talinay I terrace across the Quebrada Palo Cortado Fault. The height distribution of Talinay II terrace, from 100 m to 200 m a.s.l. is almost similar to that of Talinay I, but with a lesser amount. However, no significant differential uplift is seen for both Talinay III and IV terraces. This indicates that a growth of the Altos de Talinay had probably continued up to the middle Pleistocene, but no differential movement has occurred during the last *ca.* 300 ka after the formation of Talinay III terrace.

Based on the regional height of the Talinay IV terrace, the uplift rate since the last interglacial maximum is estimated to be *ca.* 0.2 m/ky, assuming that paleo sea level heights for stages 5e and 9 were +6 m and 0 m, respectively (Chappell and Shackleton, 1986). It is impossible to estimate the uplift rate for the older terraces because of uncertainty regarding the terrace ages and paleo sea level heights, but it was probably very much higher than the rates mentioned above, judging from the remarkably high terrace risers between Talinay III terrace and Talinay II terrace as well as between Talinay II and I terraces. This indicates also that the uplift rate markedly decreased towards the present since at least the middle Pleistocene.

SENSE AND TIMING OF FAULT ACTIVITY

The Puerto Aldea Fault is the most important main boundary fault, since it defines the eastern foot of the Altos de Talinay. This is a dip-slip normal fault with relative uplift on its western side, and is associated

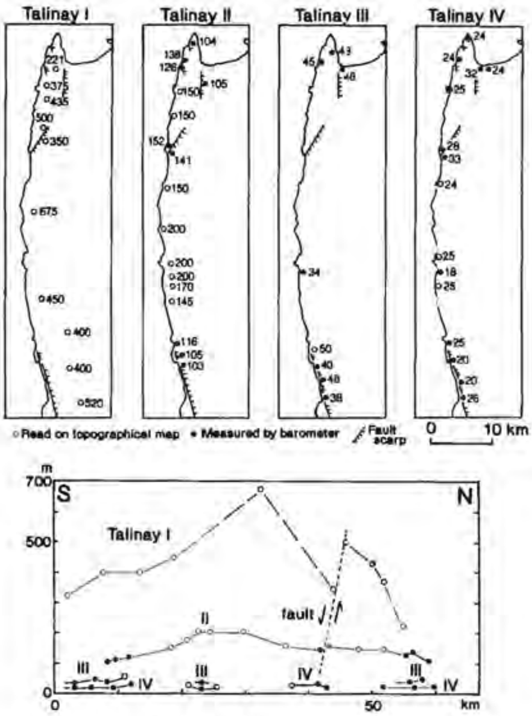

FIG. 11. Maps showing the height distribution of marine terraces in the study area (upper) and shore-parallel profiles of the height data (lower).

with the growth of the Altos de Talinay. Activity on this fault since the middle Pleistocene is expressed by a westward downtilting of the Talinay II terrace southward of Bahía Tongoy. However, no displacement is seen on Talinay III and IV terraces. Therefore, the Puerto Aldea Fault is not identified as an active fault in a strict sense, which is defined as a fault that has repeatedly moved during the late Quaternary (*e.g.*, Research Group for Active Faults of Japan, 1992). Therefore, the authors identified this fault as a Quaternary fault and predicted no future activity.

Similarly, the Quebrada Palo Cortado Fault shows progressive deformation until after the formation of Talinay II terrace, but no displacement on Talinay III and IV terraces. Thus, it is also defined as a nonactive Quaternary fault.

The Quebrada del Teniente Fault offsets both Talinay I and II terraces, with progressive displacement.

This is a normal fault with a range (east)-facing scarp, which is opposite in sense to the relief growth. No activity since the formation of Talinay III terrace was identified and therefore, it is also defined as a nonactive Quaternary fault. The reported left-lateral strike-slip along this fault was not confirmed and it is probably only an apparent phenomenon caused by differential erosion of unequally resistant rocks exposed on opposite sides of the fault.

Many north-south trending smaller faults dislocate Talinay I and Talinay II terraces on the western foot of the Altos de Talinay. They are topographically very easily identified, because they are expressed as range-facing scarps. However, slip-rate of these faults is very small (on the order of 0.01 m/ky or less). They are only secondary Quaternary faults associated with the growth of updoming of the Altos de Talinay.

A range-facing fault scarp is usually formed as a secondary antithetic fault located on the backside of a major active synthetic reverse fault, which is usually expressed as a prominent basin-facing fault scarp or flexural scarp, associated with the growth of the relief. Such reverse faults usually have a large slip-rate on the order of 0.1-0.6 m/ky with progressive displacement and have been formed under compressive stress field (*e.g.*, Research Group for Active Faults of Japan, 1992). However, the range-facing fault scarps of the study area are different from those associated with major reverse faults, because: **1-** there are no major fault scarps or flexural scarps facing westward, except for the possible tilting of the Talinay I terrace, south of Quebrada del Teniente; and **2-** at least the Quebrada del Teniente Fault is a normal fault and possibly other faults are also normal ones, while the range-facing scarps associated with major reverse faults are also reverse faults (*e.g.*, Ota et al., 1992).

TECTONIC IMPLICATIONS

It is important to note that a significant change in the pattern and rate of tectonic movement occurred some time before or during the middle Quaternary, that is, between the formation of the Talinay II terrace and Talinay III terrace. Progressive updoming with a north-south trending long axis took place until after the formation of the Talinay II terrace. The uplift rate might have been large, although the exact rate cannot be estimated. This updoming was accompanied by major faulting along the Puerto Aldea Fault and some other significant faults, such as the Quebrada Palo Cortado Fault and the Quebrada del Teniente Fault. These faults were not subsequently active since the formation of Talinay III terrace. Many other short dip-slip faults are probably secondary ones, which were formed in association with the updoming and they also have been inactive, at least, during the last *ca.* 300 ka.

These phenomena are very different from other subduction zones on the western rim of the Pacific Ocean. For example, remarkable landward tilting with high uplift rate (1-4 m/ky) is known for the coastal area of central and southwestern Japan on the overriding Eurasia Plate being subducted by the Philippine Sea Plate, or on the east coast of North Island, New Zealand facing Kermadec Trench, as a subducting plate boundary (*e.g.*, Ota and Kaizuka, 1991). In both of these areas such uplift is considered to have started after the formation of older terraces of *ca.* 300 ka and the present coastal uplift is characterized by episodic coseismic uplift, caused by activities of subsidiary faults from megathrusts at plate boundary. It is also important to note that there are no active faults in the Altos de Talinay area, whereas on parts of the above mentioned western Pacific rim there are many active faults which have been repeatedly active up to the present. These facts require different mechanism and further interpretation of tectonism on the subduction zone in Chile. It is very likely that the uplifting associated with faulting prior to middle Pleistocene was the result of the strong coupling between the Nazca Plate and the South America Plate, and that the weakening of coupling since then, resulted in a relatively stable tectonic situation in the Altos de Talinay area. Such estimated change in tectonic situation is unique in the circum Pacific subduction zones and requires more discussion on the driving forces and mechanisms leading to the weakening of the coupling between two plates.

CONCLUSIONS

The authors recognized Quaternary marine terraces at four main levels and a normal fault system around the Altos de Talinay. The older terraces (Talinay I and II) were probably formed in the late Pliocene-early Pleistocene. Their shorelines depict an updoming uplift pattern, accompanied by significant fault movements. The younger terraces, Talinay III and IV, are tentatively assigned to the oxygen isotope stage 9 and 5e, respectively, based on ESR and U-series datings in the nearby Bahía Coquimbo and Bahía Herradura areas. These two terraces are not deformed by faulting and their uplift pattern shows a rather uniform and moderate regional uplift.

Rapid doming of the Altos de Talinay chronologically coincides with active movements of normal faulting in the late Pliocene-early Pleistocene. This implies that crustal updoming associated with normal faulting resulted from regional exter sion in the upper crust. Later on, the fault movement and uplift rate have been diminishing and regional uplifting with low uplift rate has been dominant. Such a change in tectonism was probably caused by the weakening of coupling intensity between the Nazca Plate and the South America Plate.

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