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Sedimentary processes on a Gilbert-type delta in Lake Llanquihue, southern Chile

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ABSTRACT

A small Gilbert-type delta on the southern shore of Lake Llanquihue, southern Chile, was studied over a period of two months. Bottom samples were taken by scuba diving along a 10 x 10 m grid to determine the distribution of sedimentary facies. The wind direction, wave conditions, underwater current directions and the orientation of sedimentary structures were recorded on a daily basis. Observations made during fair-weather conditions indicate that neither waves nor currents have any significant effect on the bottom sediments, and that the only transport is produced by bivalves causing small avalanches on the steep delta slope. This probably prevents the oversteepening and large-scale slope collapse typical of many Gilbert deltas. Observations recorded from shore during one major storm, show an excellent agreement with wave theory and empirical predictions, indicating that storm waves can affect the whole delta front and slope. These waves break about 35 m from shore where there is a clear transition from clast-supported gravel on the inner delta front to matrix-supported gravel and gravelly sand on the outer front. The storm waves are able to transport cobbles up to 40 cm in diameter. During these events, strong lakeward-directed bottom currents enhanced by the effluent plume of the river, transport some of these clasts to the edge of the delta front, where they avalanche down to the foot of the delta. During the waning stages of the storm and shortly thereafter, dense, sediment-laden bottom currents discharged from the river mouth carry plant material down the delta slope and over the pro-delta, burying the cobbles just deposited. A single cycle of delta progradation should produce two coarsening-upward cycles, which might be confused in the rock record with two distinct phases of delta progradation.

Keywords: *Gilbert-delta, Sediment transport, Sedimentary facies, Lake, Southern Chile.*

RESUMEN

Procesos sedimentológicos en un delta tipo Gilbert del lago Llanquihue, sur de Chile. Se estudió un pequeño delta tipo Gilbert en la costa austral del lago Llanquihue, sur de Chile, durante un período de dos meses. Se tomaron muestras del fondo por buceo a lo largo de una grilla de 10 x 10 m para determinar la distribución de facies sedimentarias, y se anotaron diariamente la dirección del viento, las condiciones de oleaje y corrientes subacuáticas, además de la orientación de estructuras sedimentarias. Observaciones durante tiempos normales indican que ni las olas ni las corrientes tienen un efecto significativo en los sedimentos del fondo, y que el único transporte es producido por bivalvos causando pequeñas avalanchas en el talud deltaico. Esto probablemente evita un aumento excesivo de la pendiente y el colapso de gran escala de la misma, típico de muchos deltas tipo Gilbert. Observaciones desde la costa durante una tormenta mayor, demuestran una buena coincidencia con la teoría de oleaje y predicciones empíricas, sugiriendo que las olas de tormentas pueden afectar la plataforma y el talud deltaico entero. La zona de rompientes está a 35 m de la costa donde se observan una transición clara desde gravas clastosoportadas en la plataforma interior a gravas matriz soportadas y arena guijarrosa en la plataforma exterior. Las olas de tormentas pueden transportar guijas de hasta 40 cm de diámetro. Durante estos eventos, fuertes corrientes de fondo hacia el lago, reforzadas por el chorro efluente del río, transportan algunos de los clastos al borde de la plataforma, donde precipitan al pie del talud deltaico. Durante las etapas menguantes de la tormenta y poco después, las corrientes de fondo que salen de la desembocadura, densas y cargadas con sedimentos, transportan restos vegetales sobre el talud y prodelta, enterrando los guijarros recién depositados. Un ciclo único de progradación del delta debería producir dos ciclos granocrecientes, los cuales pueden ser confundidos con dos fases distintas de progradación deltaica en el registro sedimentario.

Palabras claves: *Delta tipo Gilbert, Transporte de sedimentos, Facies sedimentarias, Lago, Sur de Chile.*

INTRODUCTION

First described from Lake Bonneville by Gilbert (1885[1]), the deltas named after this author occur on coastlines with an abrupt change in slope. They are generally coarse-grained with a tripartite architecture:

- Gently dipping topset deposits consisting of coarse sand and gravel, commonly with abundant planar and trough cross-bedding. After being deposited, these fluvial or alluvial fan sediments may be intensely reworked by waves.
- Steeply dipping (up to 30º) foreset deposits consisting of coarse sediments, normally with abundant slumps and other structures indicating mass flow processes.
- Gently dipping bottomset deposits of fine sediments, typically with structures such as flutes generated by turbidity currents and sediment-laden water flowing close to the bottom.

Modern Gilbert-type deltas have been described from the Gulf of Corinth (Greece) by Ferentinos *et al.* (1988), from British Columbia by Prior and Bornhold (1988, 1990) and from various localities by Syvitski and Farrow (1989). Many ancient Gilbert-type deltas have also been recognized in various parts of the world, including the USA, Mexico, Greenland, Greece, Spain, and Korea (Surlyk, 1978; Postma and Roep, 1985; Postma *et al.*, 1988; Chough *et al.*, 1990; Ori *et al.*, 1991; Dabrio *et al.*, 1991; Hardy *et al.*, 1994; Horton and Schmitt, 1996; Falk and Dorsey, 1998). In Chile, Gilbert-type delta complexes in the Lower to Middle Miocene Cura-Mallin Formation (Suárez and Emparan, 1995) formed in a geologic and geographic setting very similar to the one described in this paper.

This study focuses on the surficial sedimentological processes of the Pescado Delta in Lake Llanquihue, located about 20 km east of Puerto Varas, southern Chile (Fig. 1). The delta differs from most Gilbert-type deltas described in the literature, in that it is affected from time to time by lahars that originate on the flanks of the sporadically active Calbuco Volcano. However, within the tectonic and geomorphologic context of Chile, it is very likely that such delta complexes are very common, not only in the many modern lakes and sea straits located close to volcanic centers, but also in Cenozoic deposits representing similar settings. A thorough understanding of the modern processes operating on Gilbert-type deltas in volcanic settings will therefore assist in the recognition and interpretation of these complexes in the stratigraphic record. The Pescado Delta is ideally suited for studies of this type, being small (150 x 200 m) and at a depth shallow enough (less than 30 m) for normal scuba diving. The clear water also facilitates underwater observations.

GEOMORPHOLOGIC AND CLIMATIC SETTING

Llanquihue is the largest of many lakes in the Chilean lake district, having a roughly triangular shape with sides about 50 km long. The western and northeastern coastlines are extremely irregular, whereas the southern shore is much smoother, probably due to the southerly advance of storm waves eroding and straightening the coast. The water depth reaches a maximum of about 340 m in the center of the lake and remains relatively constant throughout the year.

Two active volcanoes, Osorno and Calbuco, both exceeding 2,000 m in elevation, are located within 10 km of the northeastern and southern shores, respectively (Fig. 1). The Pescado River

[1] 1885. The topographic feature of lake shores. Annual Report (Unpublished), *US Geological Survey*, No. 5, p. 75-123.

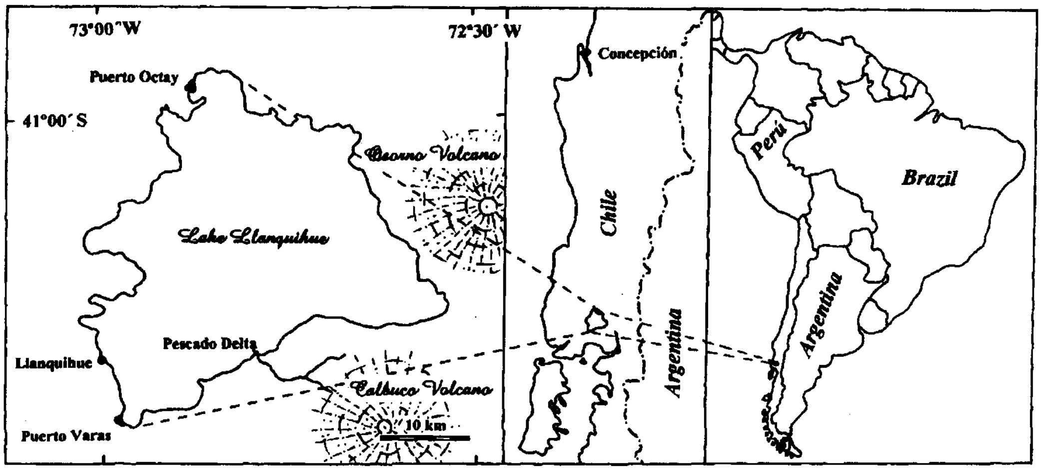

FIG. 1. Locality map showing the relation of the Pescado River with the Calbuco Volcano, which probably has an important influence on the Pescado river and delta morphology.

originates on the northwestern flank of Calbuco and has a gradient of about 10° at its origin, declining to a few degrees at its mouth.

Calbuco volcano is one of the most dangerous volcanoes of the Southern Andes (Moreno, 1998; 1999) because of the explosive nature of its eruptions, which have occurred with a mean frequency of about 19 years over the last two centuries (Petit-Breuilh, 1999). Blocky lava flows, pyroclastic flows and lahars caused by melting snow during such events are directed down the river valleys originating on the mountain flanks. A major eruption in 1929, for example, generated a lahar that clogged the lower reaches of the Pescado River (navigable up to that time) with coarse debris (Kinzel and Horn, 1983). However, lahars formed during the last major eruption of Calbuco volcano in 1961 were restricted to the area east of the volcano and did not affect the Pescado River.

The climate of the region is temperate, with temperatures commonly between 0C and 25°C and rain falling throughout the year. Summer and winter storms are accompanied by winds sometimes exceeding 80 km/h from the north and waves reaching more than 2 m in height. Torrential rain occurs mainly in summer, when the 0°C isotherm is higher and prevents the formation of snow. During such events (as occurred, for example, in May, 1995), the rivers originating on the flanks of the volcano are filled with volcanic and other debris, increasing their capacity to transport large boulders down to the shores of Lake Llanquihue (J.A. Naranjo, personal communication, 2004).

The relative frequency of volcanic eruptions and torrential rains affecting the Pescado River, implies an unstable environment causing significant changes in its geomorphology over time. Although no long-term study has been conducted of this specific river, substantial changes have been documented in the Pucón River about 240 km to the north, since the last eruption of the Villarrica Volcano in 1971 (Naranjo and Moreno, 2004).

STUDY METHODS

Fieldwork included daily observations of the wind and wave direction, as well as the wave height and period. Wind and underwater current directions were measured with thin ribbons tied every 10 cm to a 1 m long string, with a cork at one end and a 1 ounce lead sinker at the other (Fig. 2). An underwater compass was used to measure the current directions. The mean wave height was determined by measuring the 20 largest waves with a stadia rod at the point just before they broke, whereas the wave period was calculated from the time it took for 20 successive waves to reach the coast.

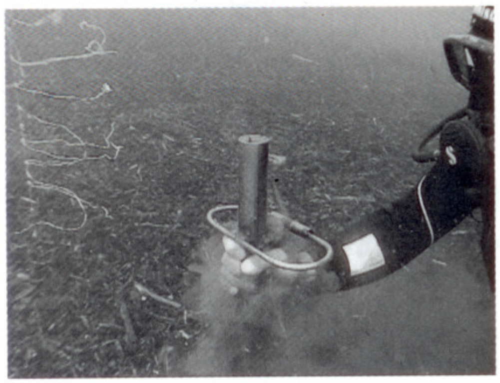

FIG. 2. Current meter employed to determine wind and underwater current directions and device used to sample bottom sediments.

Underwater fieldwork was carried out using scuba diving equipment to observe and sample the delta surface at depths of up to 30 m. During fair-weather conditions more than 45 dives, each lasting over an hour, were executed, during which the sampling grid was laid out, observations were made and 261 bottom sediment samples were taken. Storms reduced underwater visibility to nil and conditions became too dangerous for diving.

In order to position the sampling stations, a base line was set up parallel to the coast in the prodelta zone near the toe of the delta, at a depth of less than 30 m. It was secured with stakes attached to slightly submerged buoys at 50 m intervals and graduated every 10 m. Secondary sample lines, also graduated at 10 m intervals, were extended from these points to the shore, where they were staked down. The sampling stations were thus placed on a roughly rectangular grid. A telescopic alidade was used to map the shoreline and position of the stakes.

At each sampling station, the orientation of sedimentary structures, water depth and current direction were measured. Samples of 100-300 g were taken from the top few cm of the surface sediment using a 3.5 cm diameter steel tube (Fig. 2). They were sealed in pre-numbered, ziplock-type plastic bags. In the laboratory, the samples were sieved using 7 mesh sizes between –2 and 4f to determine the grain-size parameters, including the median size.

RIVER AND DELTA MORPHOLOGY

The delta morphology described here is based on depth measurements along the 10 m grid, from which 1 m isobaths were constructed (Fig. 3). The delta can be classified as a wave-dominated, Gilbert-type delta developed in relatively deep water, as attested by the fact that the delta front is separated from the prodelta by a distinct delta slope. The latter has a tangential profile (Fig. 3), which normally indicates a high bedload/total-load ratio. Deltas of this type often experience slope failure due to the fact that the delta front progrades faster than the lower delta slope, causing oversteepening (Postma, 1990).

The Pescado River is a small braided stream where it enters Lake Llanquihue and can be classified as a type A feeder system, being dominated by gravel and displaying a steep gradient exceeding a few degrees (Postma, 1990). It has a primary outlet emptying straight into the lake, as well as a lateral outlet to the east of and separated from the principal outlet by a 60 x 20 m gravel bar oriented parallel to the coast (Fig. 4). To the east of the primary outlet the coastline is, therefore, irregular with gravel bars emerging from the water, but to the west it is formed by a straight gravelly beach. The primary outlet channel is a meter deep, continuing underwater as a 20 m wide erosional feature which shallows up to about 50 m from the river mouth, where it changes into a gentle ridge, up to 50 cm high, extending partly over the outer delta front for a distance of about 30 m. This is a typical 'mid-ground' distributary mouth bar with very shallow depressions on either side where the main outlet channel bifurcates into two distributaries (Fig. 4). Such bars form where the effluent plume or jet is dominated by frictional forces (Wright, 1977), but contrary to most bars of this type it has a gentle landward dipping back and steeper lakeward-dipping

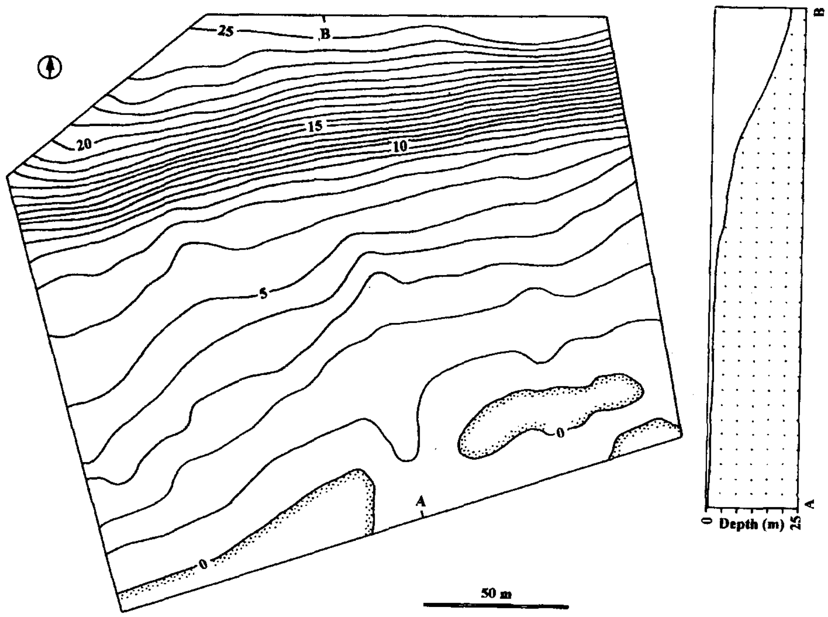

FIG. 3. Isobaths of Pescado Delta, based on depth measurements on a 10 x 10 m grid. The main outlet channel extending from the mouth of the Pescado River changes into a midground distributary mouth bar about 50 m from the shoreline, as indicated by the northward deflection of the isobaths. The steep angle of the delta slope and gentler-dipping prodelta are reflected by the contours and the longitudinal cross-section from A to B.

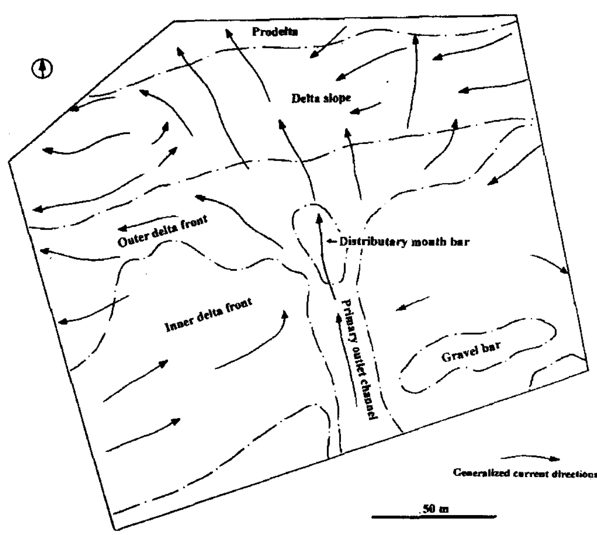

FIG. 4. Delta morphology and generalized current directions as derived from underwater current measurements and the orientation of sedimentary structures. Westward-directed currents along the delta slope and parts of the outer delta front impart an asymmetrical shape to the delta as a whole.

front, which indicates that the jet also has a fairly high inertia and turbulent nature (Wright, 1977).

The delta front (Figs. 3, 4) is somewhat elongated towards the west, parallel to the coast, its gradient also diminishing in this direction from a maximum of about 6° east of the primary outlet. It is divided into an inner and outer front based on the distribution of sediments, although there is no clear topographic difference between the two sub-environments. The delta front margin lies about 100 m from the shore at 8 m deep, from where the delta slope descends to at a depth of 20 m at a steep angle of almost 30° (Figs. 3, 5). The prodelta has a more or less constant slope of 8° where it begins at 20 m deep, diminishing smoothly toward the lake bottom at depths beyond 30 m.

FIG. 5. Delta front margin, showing steep inclination of delta slope.

DISTRIBUTION OF SEDIMENTARY FACIES

The delta plain and inner delta front are characterized by clast-supported gravels, including boulders and cobbles, which extend to a depth of between 2 and 3 m to the limit with the outer delta front. The primary river outlet and its underwater extension are filled with matrix-supported gravel and gravelly sand (at least on the surface) where they cross the coastline and the inner delta front. This gravelly zone swings around at the limit between the inner and outer delta fronts and forms a 15 to 50 m wide belt parallel to the coast (Fig. 6). The rest of the outer delta front and uppermost part of the delta slope is underlain by coarse to very coarse sand. These sands grade into coarse and medium sand on the upper delta slope to scoria, pumice, sticks and leaves on the lower delta slope and prodelta. Below the plant material, pebble accumulations can be observed.

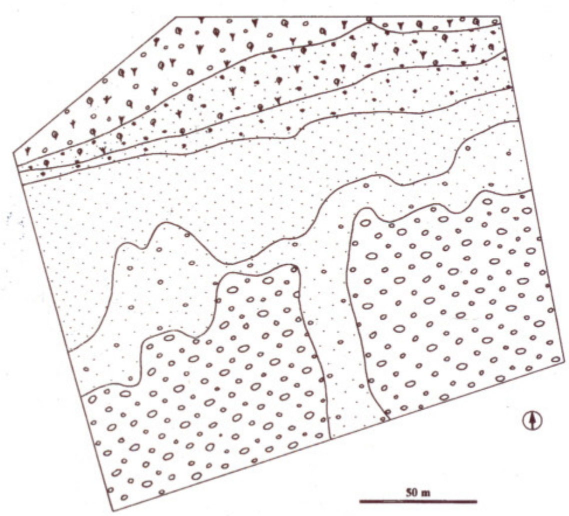

FIG. 6. Distribution of sedimentary facies over the Pescado Delta. The change from cobble/pebble gravel to pebbly sand at the limit between the inner and outer delta front coincides with the breaker zone during storms, whereas the change from sand to sand and scoria occurs at the edge of the delta front.

DISTRIBUTION OF ALGAE AND SHELLFISH

There is a clear correlation between water depth, surface sediments and the distribution of algae and shellfish over the delta front (Fig. 7). Algae occur from the shoreline to a maximum depth of about 7 m. They are confined to the clast-supported gravels of the inner delta front and the matrix-supported gravels of the transitional zone with the outer delta front. Gastropods also dominate along the western part of the transitional zone between the inner and outer delta front at depths between 2 m and 6 m, whereas bivalves (*Diplodon* sp.) are confined to the delta front margin and delta slope, at depths exceeding 7 m.

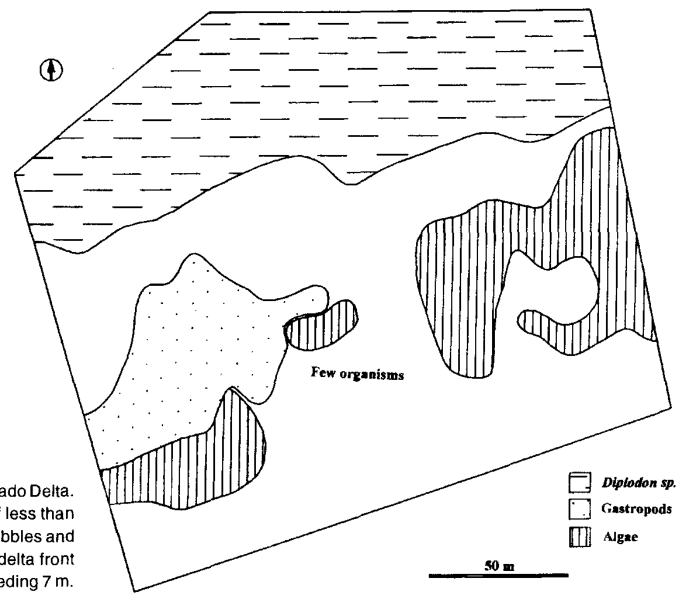

FIG. 7. Distribution of organisms over the Pescado Delta. Algae are restricted to water depths of less than 7 m where there is an abundance of cobbles and pebbles. Bivalves are confined to the delta front margin and delta slope at depths exceeding 7 m.

MEASURED CURRENTS AND SEDIMENTARY STRUCTURES

Currents measured along the grid (Fig. 4) indicate different flow systems over different parts of the delta. Opposite the primary outlet along the underwater channel/distributary mouth bar system, the flow direction is perpendicular to the coast, continuing this trend up to a depth of about 25 m even where the channel extension has no topographic expression. Where the current enters the outer delta front, however, it also expands fanlike (partly along the two distributaries), but somewhat skewed to the west. The current strength diminishes from strong and moderate up to a depth of 3 m to weak over the outer delta front and down the delta slope. East of the primary outlet on the inner delta front, currents are weak and variable with no definite trend, probably as a result of the irregular bottom topography in this area. West of the primary outlet, however, the inner delta front is characterized by weak currents flowing towards the east, which can be attributed to longshore currents resulting from incomplete wave refraction in the surf zone. The outer delta front west of the extension of the primary outlet channel shows weak coastal currents flowing towards the west, which may be part of a larger circulation pattern within the lake itself. This trend is also observed over most of the delta slope both east and west of the primary outlet channel extension and accounts for the marked asymmetry of the delta. A second, narrow zone of currents flowing straight down the delta slope is observed some 30 m east of the underwater extension of the primary channel. Its existence is confirmed by the orientation of asymmetrical ripples, sticks and crescent marks in this area. There seems to be no topographic reason for this trend, although it may be related to the earlier position of the river mouth to the east of the present primary outlet.

Sedimentary structures could only be measured in the sandy facies on the outer delta front, where they consist of wave ripples, current ripples, combined wave and current ripples and crescent marks on the upstream side of clasts. The orientation of waterlogged sticks and leaves was also measured. Current ripples are generally oriented perpendicular to the coastline and indicate lakeward-directed currents, even over the delta slope where measured currents indicate an easterly flow. This indicates that these ripples were formed during an earlier event or events (probably storms) when strong bottom currents were established perpendicular to the shoreline. Wave ripples are concentrated over the outer delta front to the west of the underwater channel/distributary mouth bar system, where current ripples are very rare. Both wave and current ripples generally have troughs significantly coarser than their crests, what suggests that they formed during conditions of relatively low sediment supply and transport rates. The segregation of sand and gravel at low sediment transport rates can lead to the formation of open-framework gravel beds (Bridge, 2003), confirming what is actually observed on the outer delta front. Sticks and leaves on the delta slope and prodelta are all oriented perpendicular to the coastline, possibly reflecting density currents flowing straight down the slope. They do not seem to be affected by the weak contour currents measured on the delta slope.

SEDIMENTARY PROCESSES

The runoff of the Pescado River is generally small, but during torrential rainfall or lahar flows from the Calbuco Volcano, it changes into a high-energy conduit. During these events, mixing of the river water with volcanic scoria and pumice transported down the slopes of the volcano into the river valley, converts the flow into hyperconcentrated, viscous mud or debris flows capable of transporting large boulders. Sediment transported by the river thus varies from clay and mud after light rain to sand and boulders exceeding 30 cm in diameter during floods and lahar flows. These catastrophic events can cause dramatic changes in the river morphology. Local fishermen report that the river shifted its mouth about 40 m to the west some 10 years ago, when it broke through a pebble bar on the beach to form the present primary outlet. The presence of concrete blocks 30 m from the shore, derived from the destruction of a bridge by a lahar, also attest to the violent nature of these volcanic events. The volcanic influence is furthermore indicated by the abundant pumice and scoria in the prodelta zone.

Observations during the study period indicate that sedimentation processes on the delta are largely controlled by storms. Currents observed and measured during normal weather periods appear to have very little influence on the surface sediments, being too weak to transport the boulders, gravel and coarse to very coarse sands on the delta front and slope.

A major storm that occurred on 9 January 2001 allowed some important observations to be made, giving some insights into the processes operative during these events. Although conditions did not allow direct underwater observations, hydrodynamic conditions can be reconstructed from measurements taken on shore during the storm, as well as observations of sedimentary structures and samples taken when conditions began to return to normal.

During the storm, a wind direction of 350° was recorded at the Pescado Delta and speeds of up to 80 km/h were reported by the local press. However, the sustained or average wind speed, to which wave formation is related, is usually much lower than the maximum wind speed. For example, Adams (2003) recorded 59 significant wind events (exceeding 32.4 km/h for more than 3 hours) on the Great Salt Lake in Utah during 1986-87. During the strongest wind event, the average of five consecutive hourly wind observations was 49 km/h, which is

78% of the recorded hourly maximum of 63 km/h. In the Lake Lahontan Basin, wind records from 1992-1999 show 203 significant wind events with a maximum of 68 km/h and average speeds ranging between 32 and 56 km/h, the last probably referring to the maximum event (Adams, 2003). The sustained speed in this case is 82% of the maximum speed, so that a 20% reduction seems to be justified as a rough way to estimate the average speed from the maximum speed. Applying this to the 80 km/h maximum speed recorded for the 9 January storm on Lake Llanquihue, the sustained wind speed should have been about 64 km/h. During the peak of the storm, a wave period of 5.6 seconds was measured by timing the arrival of 20 successive waves. A breaking wave height H_b of 2 m was estimated, with the breaker zone located about 40 m from the shore. During the storm, 2 m of the coastline was eroded, followed by the deposition of a 1 m wide gravelly beach crest parallel to the coast (Fig. 8).

The measured wave period (T) allows the following calculations to be made, bearing in mind that T remains constant for the specific wind conditions, irrespective of the water depth. The deepwater wavelength L_d is given by (Eckhart, 1952):

$$L_d = (g/2\pi)T^2 \quad [1]$$

where g is the acceleration of gravity (981 cm s^{-2}). In this case, L_d is 49 m. As waves have an influence on the bottom to a depth of half their wavelength, this means that the whole delta front and slope would have been affected by this storm.

The deepwater wave height H_d is related to the fetch distance F (*i.e.* the distance that the wind blows over open water), as well as the wind duration and speed. It is also related to the wave period. In this case, as the wind blew from 350°, the fetch distance is 30 km. Using a set of wave prediction curves of CERC (1984), as published in Adams (2003), H_d is calculated at 2.08 m. The wind stress factor U_A and wind speed U_a can be obtained as follows (CERC, 1984; Adams, 2003):

$$U_A = H_d/(0.0005112F^{0.5}) \quad [2]$$

which yields a value of 23.49 for U_A. The wind speed is calculated by:

FIG. 8. Gravel beach formed during the waning stages of a storm on 9 January 2001. At the height of the storm, the existing beach was eroded.

$$U_a = {}^{1.23}\ (U_A/0.71) \quad [3]$$

A sustained wind speed of 17.2 m s^{-1} or 62 km/h is thus obtained, corresponding to the estimated conditions.

The wavelength (L) at any water depth (d) can be related to the deepwater wavelength (L_d) by using published graphs (Wiegel, 1966). For intermediate water depths where $0.03 < d/L_d < 0.5$, this can be quantified as:

$$L = d/[2.25(d/L_d)^3 - 1.74(d/L_d)^2 + 1.245(d/L_d) + 0.0316] \quad [4]$$

The wave height H at any specific depth is related to L, L_d, and H_d (Wiegel, 1966), quantified in equation 5 for $0.03 < d/L_d < 0.3$.

$$H = H_d[-53.8(d/L_d)^3 + 35.5(d/L_d)^2 - 6.93(d/L_d) + 1.332] \quad [5]$$

Wave ripples were observed right up to the outer edge of the delta front at 8.3 m depth. Using equations 4 and 5, the wavelength L here is calculated at 40.8 m and the wave height at 1.91 m. The maximum wave orbital velocity U_m at the bottom at this depth is given by an equation of Komar (1974):

$$U_m = \pi H/[T \sinh(2\pi d/L)] \quad [6]$$

yielding 0.65 m/s.

The breaking wave height H_b is related to the deepwater wave height H_d by the following equation from Komar (1998):

$$H_b = 0.39g^{0.2}(TH_d^2)^{0.4} \quad [7]$$

A breaking wave height of 2.2 m is thus calculated, which also coincides with the observations from shore. Using an equation of Komar (1998), the breaking water depth d_b can be determined as follows:

$$d_b = H_b/[1.2\xi^{0.27}] \qquad [8]$$

where $\xi = S/[(H_d/L_d)^{0.5}]$, S being the bottom slope (tangent of the slope angle).

Using these relationships and a slope of 4° on the delta platform, the waves would break at a depth of 2.45 m at a distance of 35 m from the shore. This coincides exactly with the transition from the inner to the outer delta front, where matrix-supported gravel and gravelly sand pass shoreward into clast-supported cobbles and boulders. At this depth, the wavelength would be 27.3 m and the maximum orbital velocity 2.1 m s^{-1}. Using equations given by Adams (2003), the critical shear stress τ_c necessary to move clasts with diameter D_m over bed material with a mean diameter D_b is given by:

$$\tau_c = 0.045\rho_\gamma g D_m^{0.4} D_b^{0.6} \qquad [9]$$

For cobbles 30 cm in diameter moving over bed material of the same size, τ_c would be 2185.2 g cm^{-1} s^{-2}.

τ_c can be adjusted to account for the bottom slope S (4°):

$$\tau_{cS} = \tau_c[(\tan\phi + \tan S)/\tan\phi]\cos S \qquad [10]$$

where ϕ is given by:

$$\phi = 31.9(D_m/D_b)^{-0.36} \qquad [11]$$

For 30 cm cobbles moving over bed material of the same size, this yields 2,424.8 g cm^{-1} s^{-2} for τ_{cS}.

The water velocity required to move the clasts is given by:

$$U = 5.75\sqrt{(\tau_{cS}/\rho)}\,\log[30(D_m/2)/(3D_b)] \qquad [12]$$

which in this case is 1.98 m s^{-1} The waves of this particular storm would therefore have been able to move cobbles up to 30 cm in diameter, if all were the same size. However, it can be calculated that boulders as large as 40 cm could be transported over a bed of sand due to the diminished bed roughness. On the inner delta front, cobble sizes often exceed 50 cm, which could indicate that they were deposited by larger, earlier storms or within former outlets of the river during periods of extreme runoff or lahars, thereafter remaining more or less in place.

Strong, lakeward directed bottom currents generated during storms and periods of intense runoff are probably responsible for the asymmetric ripple marks observed over the delta front and slope. The combination of increased inflow from the river and bottom currents produced by the accumulation of water on the beach by storm waves during rainstorms would be most noticeable opposite the river mouth, where in fact the largest number of current ripples is observed extending right out to the foot of the delta slope. These very strong currents would leave only boulders and cobbles on the inner delta front, while depositing cobbles, pebbles and coarse sand on the outer delta front as the currents begin to lose strength in deeper water.

Sediment eroded from the delta front during storms or discharged by the river during heavy rainfall or lahar flows avalanches down the delta slope, some large pebbles reaching the delta toe, where they are covered by leaves and sticks accumulated during the waning stages of the storm and shortly thereafter. The plant fragments are oriented perpendicular to the shoreline and are apparently unaffected by the weak contour currents paralleling the delta slope during normal weather conditions. This suggests that they were deposited parallel to sediment-laden, cold and dense water flowing along the bottom after heavy rains, when the river outflow was still high but unable to transport pebbles to the edge of the delta front.

The concentration of scoria and pumice on the delta front margin and delta slope can be attributed to the fact that they are partly water-saturated, making them less dense than siliciclastic pebbles of equivalent size but still somewhat denser than the plant fragments occurring on the lower slope and prodelta. These clasts therefore bypass the delta front where waning, lakeward-directed storm currents are still capable of transporting them, but where the water depth increases abruptly at the front margin, the currents diminish in strength so that they are deposited. As the scoria and pumice clasts are less dense than their siliciclastic counterparts, they also have a smaller momentum, so that they do not avalanche all the way down to the foot of the delta slope.

Calculations, similar to the above, can be made for normal weather conditions, which indicate that fair-weather waves would have no influence at all on the outer delta front and slope. A typical day, for example, was 16 January when a gentle breeze blew straight from the west causing waves with a period of 2.1 s. The deepwater wavelength in this case is calculated at 6.9 m and the wave height less than 0.1 m, so that the delta would be affected only at depths less than about 3.4 m. At a depth of 2.07 m, the limit for which equation 5 is still valid, the wavelength would be 6.7 m and the wave height about 0.1 m, giving a maximum orbital velocity of 0.13 m s^{-1}. These waves would, therefore, be incapable of moving the pebbles, cobbles and boulders of the inner delta front.

One of the few processes affecting the delta during fair-weather conditions is bioturbation. The activity of bivalves (*Diplodon* sp.) on the delta slope causes a constant downward migration of sands destroying any sedimentary structures and constantly decreasing the slope. This might well maintain the equilibrium of the delta slope and prevent large-scale, catastrophic slope failure, as is often observed in other deltas of this type (Postma, 1990).

Considering the grain-size distribution over the whole delta, progradation of the latter would produce two coarsening-upward cycles, *i.e.,* from the prodelta to the foot of the delta slope, and from the delta slope to the inner delta front and beach. The basal cycle would be easily recognizable by the presence of abundant plant material, scoria and pumice, interbedded with pebbles and cobbles.

CONCLUSIONS

The observations made during this study clearly indicate that the delta is largely inert during fair-weather conditions, except for the action of bivalves on the delta slope, which probably rapidly destroys the effects of storm waves. The asymmetric shape of the delta, although clearly related to a cyclonic circulation pattern within the lake, also does not seem to be a product of fair-weather conditions, as no sediment transport was observed during underwater excursions. Large storms such as the one recorded on 9 January are able to affect the whole delta (except the prodelta) to a depth of 25 m or more. Where the waves break on the transition from the outer to the inner delta front, they are able to transport boulders up to 40 cm in diameter and possibly larger under extreme storm conditions. It seems likely that the cyclonic lake circulation is also enhanced during storms, but that any sedimentary structures indicating a westward direction of transport are rapidly destroyed by the action of bivalves on the delta slope and by hyperpycnal, lakeward-directed flows shortly after these events.

The grain size distribution over the whole delta, ranging from clast-supported gravels on the inner delta front to matrix-supported gravels and gravelly sand on the outer delta front, very coarse to medium sand on the delta slope, pebbles interbedded with plant material and scoria on the upper prodelta and finally finer sands and silts on the deeper prodelta, would give rise to two coarsening-upward cycles during a single cycle of delta progradation.

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