Quaternary lacustrine braid deltas on Lake General Carrera in southern Chile

Deltas entrelazados lacustres del Cuaternario en el lago General Carrera, sur de Chile

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ABSTRACT. A series of Quaternary lacustrine braid deltas on the shores of Lake General Carrera in southern Chile formed as a result of falls in lake level. Each delta comprises two components, the delta fan and the beach embayment, each in turn comprising an onshore subaerial and an offshore subaqueous element. The delta fans have a classic Gilbert form with a braided delta top and a steeply inclined delta front. Adjacent to the fans are concave beach embayments that formed parallel with the deltas as they prograded into the lake. The delta sediments consist predominantly of matrix- and clast-supported gravéis to a total composite thickness exceeding 400 m. The depositional environments are dominated by ephemeral river flooding and by storm-driven waves. Beach sediment is sorted, rounded, winnowed and transported alongshore by waves to fill the beach embayment with ridges of very well sorted and well-rounded gravel. A gently-dipping shoreface platform occurs up to 100 m offshore between the beach and the brink point. From the brink point, in water depth of about 8 m, sediment cascades down the steep delta front slope to form long foresets extending to the lake floor. The sedimentary successions therefore wedge in the opposite direction from those of tectonically controlled basin margins where fan growth keeps pace with basin subsidence.

Key words: *Lacustrine braid deltas, Sedimentary environments, Sedimentary facies, Chile.*

RESUMEN. Una serie de deltas entrelazados lacustres, pertenecientes al Cuaternario, ubicados en las costas del lago General Carrera, en el sur de Chile, se formaron como resultado de caídas en el nivel del lago. Cada delta consta de dos componentes: el abanico deltaico y la zona de embahiamiento. Cada uno de ellos tiene, a su vez, un elemento subaéreo costero y un elemento subacuático. Los abanicos deltaicos tienen una forma Gilbert clásica con una parte superior de ríos entrelazados y un frente deltaico empinado. Adyacente a los abanicos aluviales existen bahías cóncavas de playa que se formaron de manera paralela a los deltas a medida que estos prograradon hacia el lago. Los sedimentos deltaicos consisten predominantemente de gravas matriz y clastosoportadas con un grosor total compuesto que excede los 400 m. Los ambientes deposicionales están dominados por inundaciones efímeras del río y por olas de tormenta. Los sedimentos de playa están seleccionados, redondeados y fueron

transportados a lo largo de la costa por las olas para rellenar el embahiamiento de la playa con dorsales de gravas muy bien clasificadas y redondeadas. Una plataforma del 'shoreface' de baja pendiente ocurre hasta 100 m agua adentro, entre la orilla y el borde. Desde el borde del lago, en el agua hasta los 8 m de profundidad, el sedimento cae en cascadas por la empinada pendiente del frente deltaico para formar grandes 'foresets' que se extienden hacia el fondo del lago. La sucesión sedimentaria se acuña, en consecuencia, en una dirección opuesta a la de aquella, de márgenes de cuenca controlados tectónicamente ('brink point'), donde el crecimiento de los abanicos mantiene un equilibrio con la subsidencia de la cuenca.

Palabras claves: *Deltas entrelazados lacustres, Ambientes sedimentarios, Facies sedimentarias, Chile.*

1. Introduction

A chain of proglacial lakes fringes the eastern side of the southern Andes Mountains in Chile bet-ween 3 9 and 52°S. The largest, known as Lake (Lago) General Carrera in Chile and Lake Buenos Aires in Argentina (Fig. 1), is 150 km long and 10 to 20 km wide. It is the third largest lake in South América (with an área of 1,900 km^2) and one of the deepest on the continent with a depth of about 600 m.

The lower sections of the Las Dunas and Los Maitenes rivers on the south-eastern shores of the western end of the lake are distinguished by a re-markable series of seven superimposed lacustrine deltas (Figs. 2, 3, 4 and 5). These deltas formed as the lake level partly drained from 650 m to 201 m above sea level in a punctuated sequence of events over the past 13,000 years (Bell, 2008). The deltas form a series of flat-topped steps extending inland from the present lake (Niemeyer *et al.,* 1984; De la Cruz and Suárez, 2006) (Figs. 2 to 7). The present-day active delta is numbered one onthe figures, with progressively older abandoned deltas numbered from two to seven.

The modern sediments provide a good exemplar for similar deposits in the geological record because there has been little human impact in this remote área.

The present study, which emphasises the morphology and sedimentology of the Las Dunas River deltas, was undertaken during 10 weeks of field work. Field observations were supplemented by the study of aerial photographs taken in 1970 by the Fuerza Aerea and topographic maps of the Instituto Geográfico Militar of Chile.

FIG. 1. Location map showing the study area on the southeast shores of Lake General Carrera. To the west of the lake are the Andes Mountains and the North Patagonian Icefield. To the east are terminal moraines and the Argentine plains.
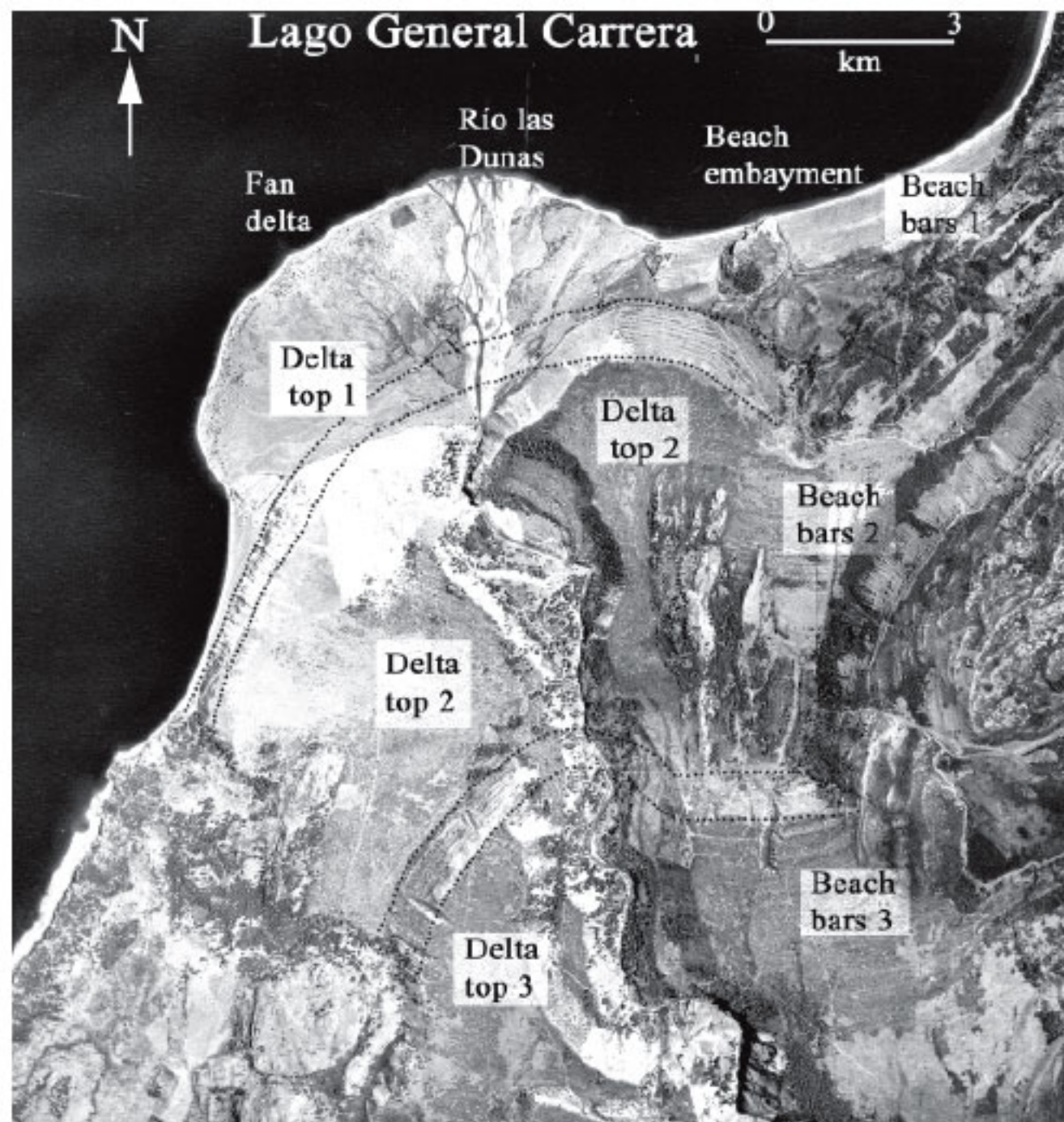
FIG. 2. Vertical aerial photograph CY01261 taken in 1970 by the Fuerza Aérea de Chile showing lacustrine deltas of the Las Dunas River. The active fan with its adjacent flanking beach embayments are backed by the flat-topped abandoned deltas 2 and 3.
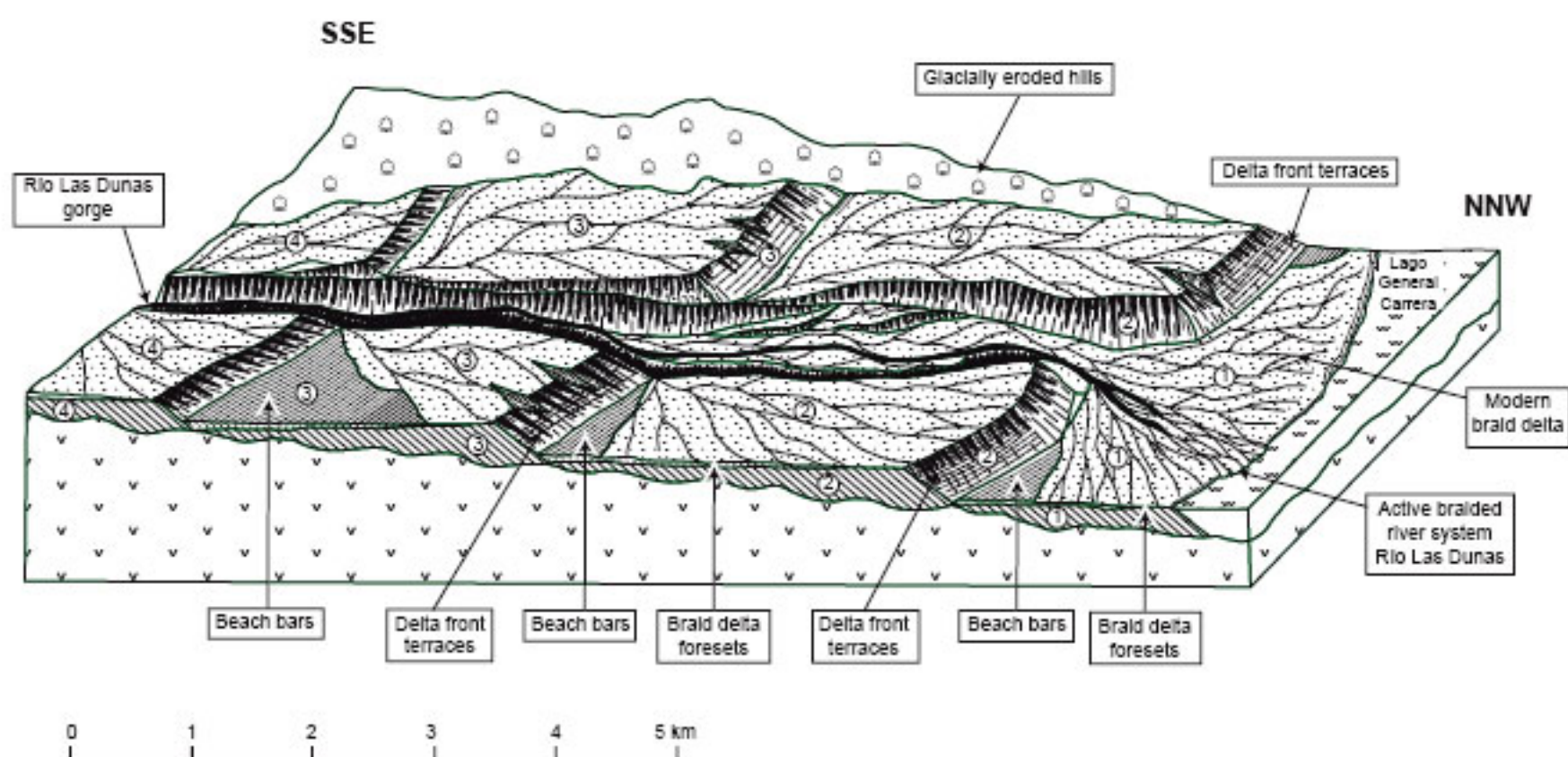
FIG. 3. Block diagram of the lacustrine deltas of the Las Dunas River based on aerial photographs taken in 1970 by the Fuerza Aérea de Chile.
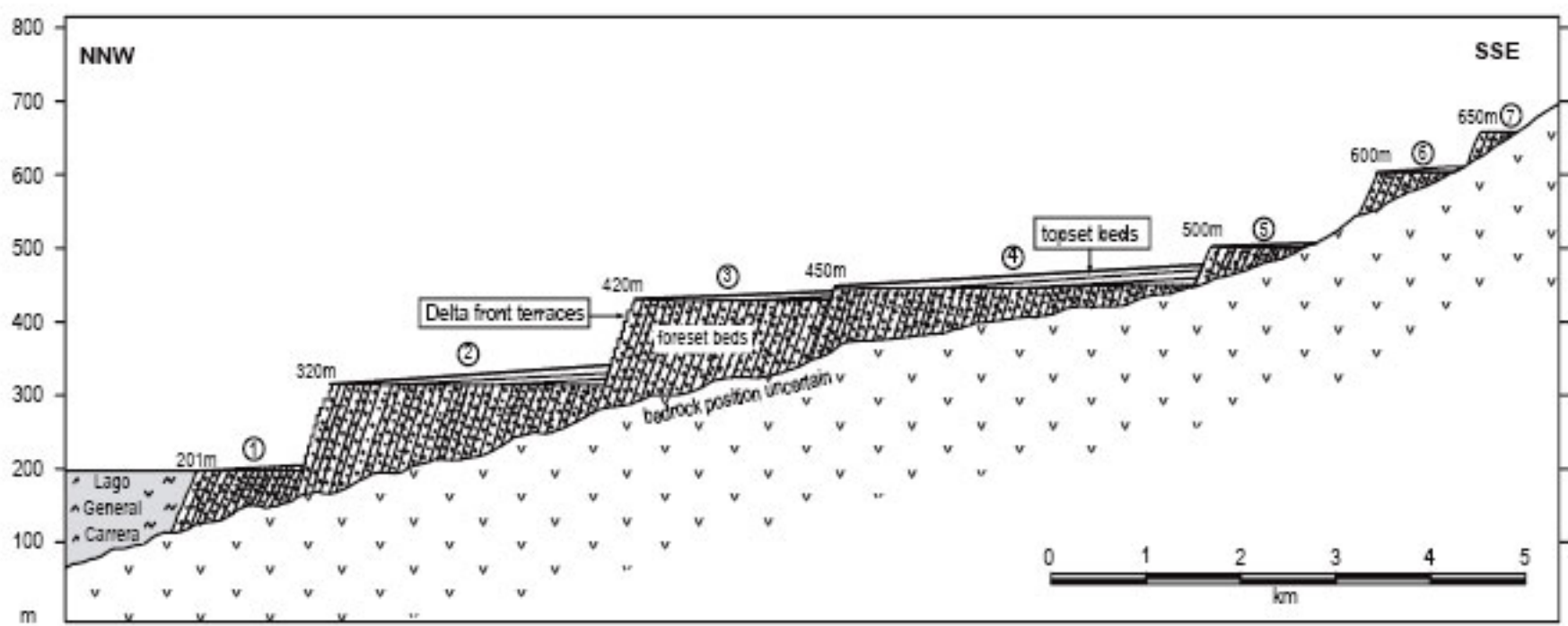
FIG. 4. Cross section diagram of the deltas of the Las Dunas River.

FIG. 5. Deltas of the Los Maitenes River. Apex of delta 1 in left foreground. Delta 2 forms the flat-topped plain in the centre left.

FIG. 6. Delta fan of the active delta of the Las Dunas River in the right foreground. The flat delta top and sloping delta front of delta 2 on the left. Lake General Carrera and the Andes Mountains in the background.

FIG. 7. Steeply-sloping delta front and flat top of abandoned delta 2 cut by an erosive valley. Braided top of delta 1 in the foreground.

2. Lacustrine Fan Deltas

The lacustrine deltas of Lake General Carrera have features characteristic of both fan-deltas and braid deltas. Fan-deltas form where alluvial fans prograde directly into standing water fromadjacent highlands; and lacustrine braid deltas are fan-sha-pedbodies of coarse-grained sedimentproducedby the progradation of braided fluvial systems (Bow-man, 1990; HamptonandHorton, 2007; Hortonand Schmitt, 1996; McPhersoneí a/., 1987, 1988; Nemec *et al.,* 1984; Nemec and Steel, 1988; Ricketts and Evenchick, 2007). Braid-deltas are non-tidal, but their geographical and sedimentary characteristics resemble those of marine fan deltas (Bornhold and Prior, 1990; Córner *et al.,* 1990; Ethridge and

Wescott, 1984). The deltas onLake General Carrera bear a cióse resemblance to those of Lake Bonneville, Utah, USA (Gilbert, 1890; Lemons and Chan, 1999;Oviatte *et al..*, 1994).

3. Geomorphology of Lake General Carrera and surrounding áreas

During Pleistocene times the massive Patago-nian Icefield blanketed the southern Andes (Clapperton, 1993; Heusser, 2003; *Yíultonetal.,* 1994). Glaciers scoured out deep valleys as they flowed eastwards from the icefield towards the Atlantic Ocean. Lake General Carrera occupies one of these glacial valleys. It is surrounded to the west by 4,000 m high mountains capped by the shrunken remnants of the icefield (Fig. 1). The lake broadens out and shallows on the Patagonian plains towards the east in Argentina, where it is rimmed by arcuate terminal and recessional moraines, dated atbetween 760,000 and 16,000 years BP (Kaplan *et al,* 2005). The lake is drained towards the south-west in Chile by the Baker River as it flows through a deep gorge through the Andes Mountains and into the Pacific Ocean. Before the opening of this gap through the mountains a much larger icedammed lake named the predecessor lake (Bell, 2008) drained eastwards via the Deseado River into the Atlantic Ocean.

About 13,000 years ago the ice dam at the western end of the predecessor lake melted (Glasser *et al,* 2004) and produced punctuated drops in the lake level recorded by the fans of the present study (Figs. 2 and 3) (Bell, 2008).

The timing, nature and sequence of Quaternary events in this little-studied región are poorly cons-trained and understood (Bell, 2008). Deltas six and seven probably formed about 13,000 years ago. Delta number two had built out into the lake by 8.5±0.7 kaBP andpossibly as long ago as 12.2±1.5 ka BP. The drop in lake level leading to the forma-tion of delta number one occurred after 6.2±0.8 ka BP (Bell, 2008).

4. Geographical and sedimentary features of the deltas

The Las Dunas River is about 30 km long, with a steep profile exceeding 25 m km^1 in its lower sections. Numerous short tributarles feed the dee-ply-incisedvalley. The river descends from 2,250 m in mountains which have lower slopes blanketed in a dense vegetation of trees, bushes, grass and moss. Rocky screes cover the mountain sides above a sharply-defined tree line at about 1,250 m. The present-day river catchment has small permanent snow and ice patches but no active glaciers. During normal flow the clear waters transpon little sediment, but periodic floods produced by storms and spring snow melt, transpon heavy loads of predominantly coarse-grained sediment. There is no recorded data on the frequency or intensity of these floods or the sediment flux. Likewise there is no published record of local weather conditions. The región is very stormy, with frequent high winds, predominantly from the west. Precipitation in the form of rain and snow is high. Seasonal and storm-driven fluctuations in the lake level are about two metres.

The descriptions of McPhersoneí *et al.* (1987) emphasised the morphology and sedimentology of the subaerial component of deltas. However, estimates of sediment volume on the Lake General Carrera deltas

suggest that an overemphasis on the subaerial section is likely to be misleading in interpreting the geological record. Although the braided fan surface is the most obvious morphological feature, forming two thirds of the subaerial exposures, its deposits comprise less than 20% of the sediment volume of the delta complex. More significant in terms of volume are the deposits of the beach, the offshore shoreface platform and in particular the foresets of the delta front, which together comprise about 70% of the total. Deposits transponed alongshore by oblique waves into the beach embayments in the lee of the fan form a further element of about 10% of the total sediment volume.

5. Morphology and sediments of the deltas

The deltas are characterised by two main environments, each with a distinctive morphology, sedimentary facies or facies assemblage and depositional processes. Each environment has a subaerial and a subaqueous element, separated by a beach. The first of the main environments is the semi-circular delta fan, traversed by a radiating pattern of braided river channels (Figs. 2, 3 and 9). These fans are convex towards the lake with a semi-circular shape and a radius of between one and two kilometres.

The composite sediment thickness of the seven superimposed deltas of the Las Dunas River exceeds 400 m (Fig. 3), with the steeply-dipping front of each of the larger deltas more than 100 m in height. The deltas are classified as type-A shallow-water classic Gilbert-type deltas in the scheme of Postma (1990) with characteristic features of flat-tops, a fan-shape and steep fronts.

The second environment is the beach embayment, gently concave towards the lake and backed by a gently sloping plain characterised by semi-continuous gravel ridges, in the lee on either side of the fan (Figs. 2, 8 and 9).

The present-day active delta fan environment can be subdivided into subaerial onshore and suba-queous offshore components, separated by a beach (Figs. 9 and 10). The subaerial component is the gently sloping delta plain or delta top, characterised by a fan of braided channels with active and inactive tracts. No underwater observations were made during the present study but the observations of Rojas and Le Roux (2005) suggest that the subaqueous component has a shallow portion, the shoreface plat-form, sloping at about 6°, and extending up to 100 m offshore. Observations on the abandoned deltas of the present study indicate that the steeper delta front or Gilbert foreset slope is inclined at about 30° and extended to a water depth of about 100 m.

The beach environment has an onshore section of a ridged gravel plain of abandoned beach bars (Fig. 8) and a presumed offshore section of a shoreface platform and delta front with a morphology similar to that of the delta fan.

The grain size of the clastic debris of the deltas varíes from boulders to clay, with a great predominance of coarse-grained material. The composition of the sediment on the delta top, reflecting the rocks in the provenance, is 70% Mesozoic felsic volcanics, 20% Palaeozoic quartz mica schist and vein quartz, and 10% Tertiary marine sandstone (Bell and Suárez, 2000). The abrasive effect of wave reworking means that the proportion of the harder quartz-rich schist and vein quartz increases to about 50% in the beach gravels.
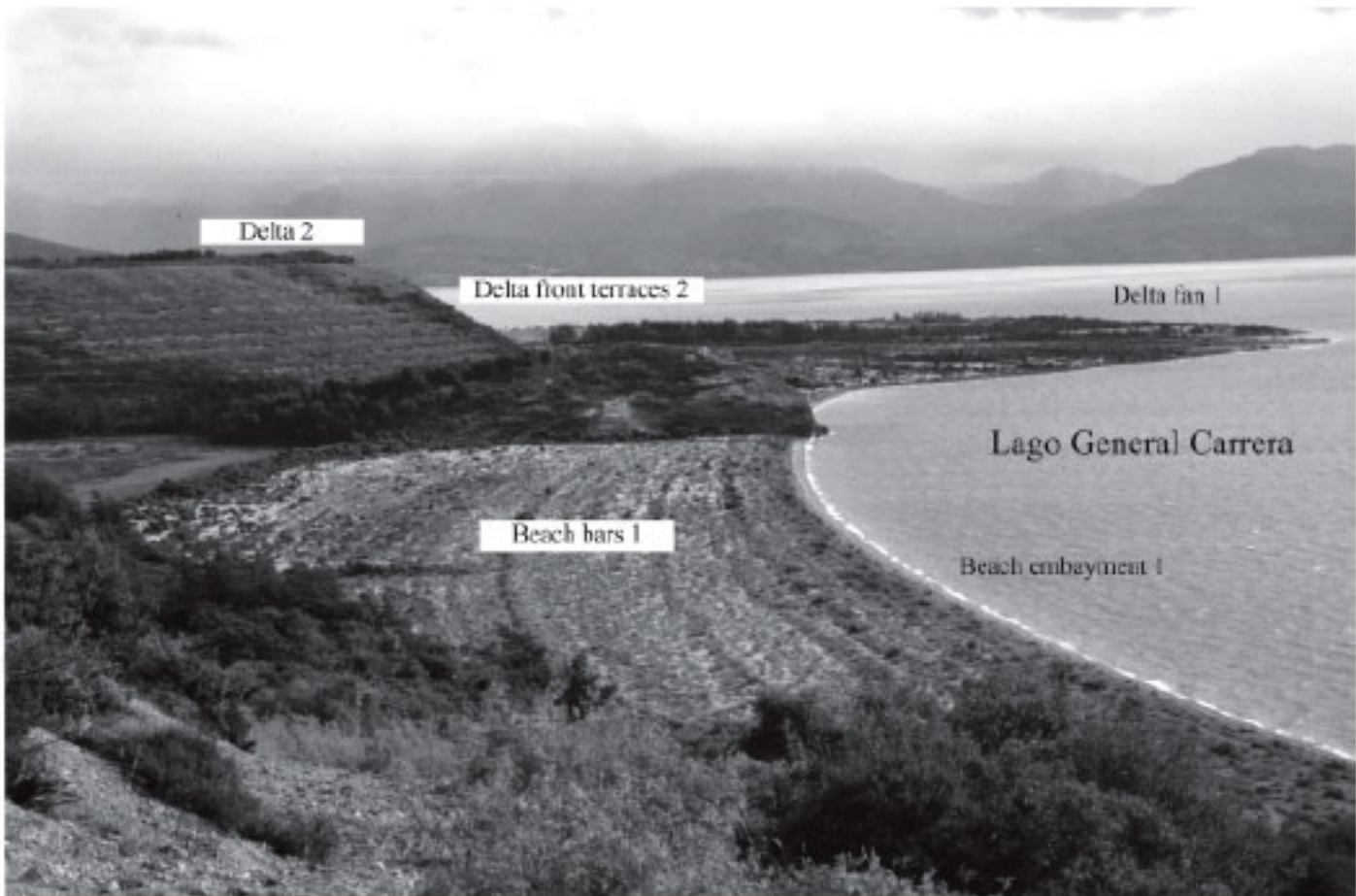
FIG. 8. Fan of delta 1 jutting into the lake with the beach embayment and beach bars in the foreground. The flat top and steeply-inclined delta front slope of delta 2 in centre left.

FIG. 9. Diagram showing the nomenclature of the morphological components of deltas 1 and 2.

FIG. 10. Cross-section of an active delta fan showing the subaerial delta top and the subaqueous delta front that is subdivided into the shoreface platform and the delta front slope.

6. Subaerial onshore section of the delta fan

The flat delta fan top surfaces dip gently towards the lake with a regular gradient of less than 1 º; a drop of about ten metres in each kilometre. The present-day fan of the Las Dunas River has a radius of 1.3 km and covers an área de about 2.5 km². The fan has a single point of input, controlledby outcrops of basement rocks. Periodic avulsión of the braided river (probably on a time scale of hundreds of years) near the point of input has produced an overlapping sequence of active and inactive tracts fanning out across the delta. The active tract of the present-

day fan, indicated on aerial photographs by an absence of vegetation (Fig. 2), is 250 to 500 m wide and occupies about one eighth of the fan surface. The braided channels are a few metres wide, weaving berween low elongated diamond-shaped bars up to several hundred metres long (Fig. 11). The poorly sorted, well-rounded to subangular sediment ranges from cobbles (up to 200 mm) to coarse sand. Finer material is deposited in pools and cut off channels during periods of low river flow. Over-bank splays of coarse sediment formfan-shaped deposits along-side the active tract during flood events (Fig. 12). Where the active tract reaches the lake it forms a bulge protruding about 150 m into the lake (Fig. 13). The river mouthis characterisedby islands and narrow beaches of gravel and coarse sand.

The outer edge of the inactive sections of the present-day subaerial fan is fringed by a 10 m wide gently sloping beach (Fig. 14) comprising well to poorly sorted gravel and coarse sand. The lower part ofthe beach, where waves break during normal weatherconditions, is armoured with a 5 m wide lag of well-sorted and tightly-packed cobbles. Inland from the beach there is a broad, ridge of gravel. 1 to 2 m high, and coarse sand, picked out on air photographs by dark-coloured vegetation (Fig. 13). Inland from this ridge there are shallow muddy vegetated swamps. Similar fine-grained sediments fill the one to two metre deep abandoned braided channels on the fan surface.

FIG. 11. Braided channels and bars of the delta top during normal river flow.

FIG. 12. Channel with overbank splays near the apex of the active delta fan. Delta 2 forms the flat-topped vegetated ridge beyond the river.

FIG. 13. Bulges of the delta fan front. Dark-coloured vegetation marks the wash-over ridge behind the beach and swamps in abandoned channels.

FIG. 14. Beach on the delta fan front armoured with a lag of wave-winnowed gravel. A storm wash-over ridge is inland from the beach.

7. Subaqueous offshore section of the delta fans

The subaqueous offshore morphology of the active deltas is illustrated diagrammatically in figure 10. No underwater observations were made during the present study, but the abandoned deltas providedevidence of the subaqueous sediments, environments and processes. Further evidence of underwater development was inferred by comparison with studies of a similar delta on lake Llanquihue in southern Chile by Rojas and Le Roux (2005).

In the deltas of lake Llanquihue, extending about 100 m offshore and to a depth of about 8 m. is a gentle slope with a máximum inclination of about 6º (Rojas and Le Roux, 2005), called here the delta front shoreface platform. The surface exhibits both shallow erosión channels and depositional bars; sediments are matrix and clast-supported gravéis, gravely sand and coarse sand, colonised by algae and gastropods (Rojas and Le Roux, 2005). Observations of the abandoned deltas of the present study indicate that the shoreface platform is sharply terminated by the delta front brink point, a well-defined and sharp boundary marking the top of the steep delta front slope (Fig. 18). The delta front slope of about 30° (measured on abandoned deltas of the present study) forming the foresets of the Gilbert delta, is the angle of repose of gravel and coarse sand.

FIG. 15. Beach embayment with storm ridges. Rotten wood on the inner ridges indicates that wash-over ridges form during exceptional storms.

FIG. 16. Poorly-sorted matrix supported gravels of Facies 1.

FIG. 17. Matrix and clast supported gravels of Facies 1 deposited in braided channels.
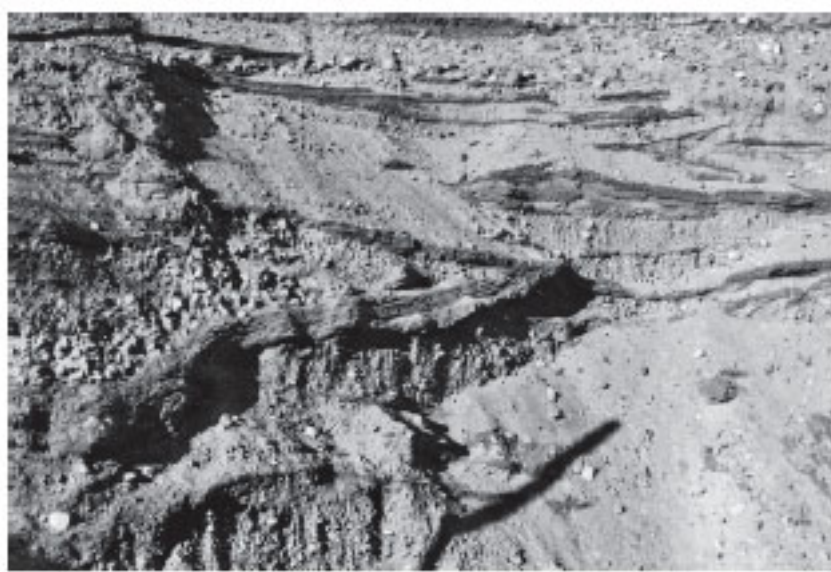
FIG. 18. Drapes of sand blanketing gravel in small irregular channels.

8. Beach embayments

Gravel beaches up to 2 km long backed by gravel plains fringe the embayments on either side of the delta fans (Figs. 8 and 15). Similar beach embayments, gently concave towards the lake, are characteristic of otherlacustrine deltas inthis región (Gilli *et al*, 2005). Bowman (1990) and Klinger *et al.* (2003) illustrated comparable beaches alongside lacustrine fan deltas of the Dead Sea. However, detailed descriptions of the morphology and sediments of these beach embayments have apparently not previously been published.

The embayments are larger on the eastern, downwind or lee side of both the present-day and abandoned deltas (Figs. 2 and 9). The present-day beaches form the front of gravel plains that extend inland for about 1 km (Fig. 8). The innermost section of the beach embayment east of the delta fan of the Las Dunas River is a vegetated muddy swamp formedbehind a spit during early stages of development of the fan delta. The ridged gravel plainfilling the beach embayment in front of the spit consists of a series of parallel one-metre high beach or swash bars (Renaut and Owen, 1991) spaced 10 to 25 m apart (Figs. 8 and 9).

The 10 m wide beach at the lake shore of the beach embayment is marked by very continuous small, low ridges of gravel, 1 to 2 m apart and rising in a series of steps to a height of about 2 m (Fig. 15). The ridges are asymmetrical, with a beach face sloping at 30°, near the angle of repose of the sediment, and a landward-dipping backshore berm with a slope of between 2 and 10°. Behind and above the beach there are 1 m high wash-over bars.

9. Sedimentary facies

The sedimentary facies of the Las Dunas River lacustrine deltas form a distinctive assemblage, characterised by coarse-grained clastic material (Fig. 16). Facies 1 and 2 are gravel-dominated successions characterised by poor-sorting. Facies 1 is cross-bedded with abundant channels (Fig. 17) whereas Facies 2 features long, straight and parallel bedded foresets (Fig. 18). Facies 3 com-prises well-sorted beach gravéis. Mudstones of Facies 4 form a very minor component of the total sediment volume. No measured section were made during the present study due to the unconsolidated nature of the material and the uniformity of the lithologies.

9.1. Facies 1: Poorly sorted gravel and coarse sand, with some finer sand and mud

Facies 1 consists mostly of lithofacies Gms, Gm and Gt of Miall (1977, 1978, 1984). It is characterised by discontinuous subhorizontal bedding with abundant channels and metre-scale cross-bedding (Fig. 17). The facies has a máximum thickness of about 20 to 30 m. The sediments were deposited in three subenvironments: the braided rivers of the delta fan top; the shallow offshore section of the delta front; and the delta front beach. They comprise an estimated 10% of the total sediment volume.

The sediments and sedimentary structures are very variable. Most clasts are pebble and cobble size, with a matrix of granules and coarse sand. Gravéis are both clast and matrix supported (Fig. 16) with alternations of coarser and finer beds. The material is poorly to very poorly sorted with little fine sand or mud. Clasts are moderately to well-rounded with a high sphericity and no obvious imbrication. Beds are 0.2 to 1.0 m thick, very discontinuous and cutby abundant channels. Cross-bedding has a complex, tabular and irregular form, with variable orientation (Fig. 19). Drapes of fine sandblanketthe gravéis in small irregular channels (Fig. 18).

Facies 1 is a complex association representing a range of lithologies and sedimentary structures deposited by a complex interplay of processes in the three sub-environments. The present study was insufficiently detailed to differentiate the characteristic features of each subenvironment and to sub-divide the sediments into a more complex facies association. The materials, environments and processes comprise firstly fluvial material forming gravel sheets and lags in braided channels and bars. and as overbank flood splays produced by the traction and mass flow of rivers during flood events on the delta top. Secondly, an armoured lag of cobbles resulted from

winnowing on gently sloping beaches backedby storm wash-over ridges. Thirdly, gravels and sands of the shoreface platform were transported by strong lake-ward directed bottom currents during river flooding and the wave reworking of major storms (Rojas and Le Roux, 2005).

9.2. Facies 2: Poorly sorted gravel and coarse sand with large-scale, steeply dipping pla-nar cross bedding

Facies 2 forms units up to 100 m thick and it comprises about 60% of the total sediment volume. It has the same lithological characteristics as Facies 1. It is predominantly matrix supported and is cha-racterised by steeply dipping (about 30°) foresets (Fig. 19). These foresets are straight and continuous for up to 10 m down slope. Poorly defined beds and laminations vary between 20 and 300 mm in thickness, with boundaries that merge into one another Some beds fine upwards. No imbrication is apparent due to the spherical shape of the clasts.

9.3. Facies 3: Well-sorted and rounded pebble and granule gravéis

Facies 3, comprising about 10% of the total volume of sediment, has very distinctive characteristics. Most of the material is very well-sorted and well to sub-rounded cobbles and pebbles with little sand (Fig. 20). The largestpebbles are 50 mmindia-meter, with an average of about 20 mm. Clasts have the same composition as those of Facies 1 and 2, al-though harder rock types (particularly vein quartz) are more abundant. The clast supported material is much better sorted and better rounded than that in Facies 1 and 2. The bedding is diffusely stratified with poorly defined layers between 20 and 200 mm thick. Beds are sub-horizontal, parallel and conti-nuous when viewed normal to the shoreline (Fig. 21) but are discontinuous, with tabular lake-ward dipping cross bedding, when viewed perpendicular to the shore.

9.4. Facies 4: Organic-rich muddy sediments

Organic-rich muddy sediments of Facies 4 form less than 1% of the total sediment volume. No out-crops were recorded in the abandoned deltas but swampy, muddy and densely vegetated áreas occur behind the spit at the back of the beach embayment and in the inactive braided distributary tracts of the active delta fan (Fig. 13).

FIG. 19. Contact at the brink point between horizontally-bedded gravels of the delta top and steeply inclined foresets of the delta front slope.
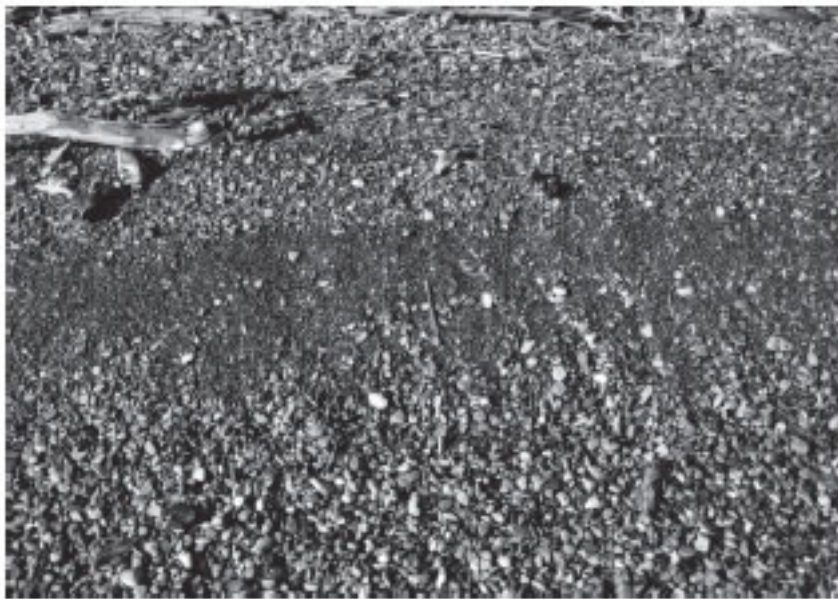

FIG. 20. Well-sorted and well-rounded beach gravels of Facies 3 in a beach embayment.

FIG. 21. Parallel-bedded beach gravels of the beach embayment viewed perpendicular to the shore.

10. Depositional Environments and processes

The weather at the western end of Lake General Carrera is dominated by strong winds and heavy rainfall. The sediments are predominantly the product of the interplay of high rates of alluvial flow during flood events and storm-driven waves on the shores of the non-tidal lake. There is little sediment movement during normal river flow or fair weather and almost all sediment movement on the delta top occurs during floods. Coarse material is deposited in the river channels and bars and as overbank splays (Figs. 11 and 12) to form Facies 1. As water levéis fall, sand is deposited in cut-off channels. A small amount of mud from overbank flooding settles from suspensión to form Facies 4. Braided streams deposit some material on the delta top but most is transponed across the delta to the lake margin (Bardaji *et al.,* 1990).

There is no data from the present study to indícate the processes operating on the shoreface platform offshore from the lake margin. However, a comparison with the studies of Rojas and Le Roux (2005) indícate that storm waves, together with lakeward-directed bottom currents enhanced by the effluent plume of the river, transpon material to the brink point from where it cascades down the slope of the delta front into deeper water by mass flow avalanching. These Gilbert foresets of Facies 2 form at the angle of repose of the sediment (Fig. 10) (Nemec, 1990; Nemec *etal.,* 1984; Nemec and Steel, 1984). Observations of the abandoned deltas onLake General Carrera indicate thatthe surface of the delta front is relatively smooth with an absence of erosive channels or slump scars. This suggests that mass flow avalanching was in the form of a semi-continuous showerof material. As inthe case in Lake Llanquihue, the activity of bivalves probably causes a cascade of sediment during normal weather conditions (Rojas and Le Roux, 2005). No fossils were found during the present study.

Waves transport gravel laterally from the delta front along the shoreline onto the beach embay ments to deposit the gravéis of Facies 3. Observations of clear, sediment-free water during the present study indicate that the sediment is only transponed by breaking waves along the shore and not in deeper water during quiet weather and minor storms. During major storms material is thrown inland to form 1 to 2 m high wash-over ridges on both the fans and the beach embay ments. In normal weather and small storms, the waves break on the beaches, but the larger waves of major storms break about 100 m offshore where they presumably transport sediment across the shoreface platform.

The southeastern shores of Lake General Carrera are oblique to the prevailing westerly winds and the beaches are dominated by wave processes. The fetch of about 20 km is sufficient to raise large waves (Massari and Parea, 1990; Renaut and Owen, 1991) which have a significant effectboth onthe morphology of the lakeshore and the characteristics of the beach sediments. All the material of the beach em-bayments (Figs. 15, 20 and 21) has been winnowed from the beaches of the delta fan and transponed by long-shore drift driven by the impact of the oblique waves (Otvos, 2000). The larger área of the beach embayments east of the fans reflects the predominantly easterly transport of material. Wave action rounds and sorts the sediment, with winnowing action removing the finer material and producing the well-sorted gravéis of Facies 3 (Bourgeois and Leithold, 1984; Wright and Coleman, 1973;Wright, 1978). As the finer gravel is transponed away from the fan it leaves an armouring lag of tightly packed and well-sorted pebbles (Fig. 14).

The ridges atthebackof thepresent-day beaches of the beach embayments (Fig. 15) are the product of storm wave action. The fronts of the ridges are blanketed with beech wood brought down by rivers in flood. The woodenbranches on the inner section are rotten, suggesting, by comparison with the condition of wood used for house and fence-building in the área, an age of more than 50 years. This indicates that storms sufficiently large to produce the larger ridges are very rare events. The parallel systems of semi-continuous ridges on the plains behind the beach embayments (Fig. 8) provide a record of the progradation of the front of the embayment.

The effects of a major storm on a beach on Lake Llanquihue was recorded by Rojas and Le Roux (2005). Winds up 80 km per hour with a sustained speed of about 64 km per hour produced waves with a height of 2 m, breaking about 40 m offshore, presumably at the brink point of the delta front. At the height of the storm 2 m of the

coastline was eroded, with a 1m-wide storm beach formed parallel to the coast.

No prodelta or bottom set sediments were recorded during the present study. Any fine material in suspensión in the flooded rivers is carried offshore into deeper water as a sediment plume. Isolated occurrences of rhythmically laminated shales, interpreted as varves or annual cycles of sedimentation deposited in the proglacial lakes, are common at other locations in the regi\u00f3n. They represent the eroded remnants of more extensive deposits(Sylwan, 1990; SylwanandBeraza, 1990; Kaplan *et al,* 2004) deposited when the lakes were much larger than at present and, presumably, during a time when more abundant fine sediment was provided by the outwash of silty or muddy glacial rivers.

11. Delta growth

Variations in vegetation cover; climate related changes in precipitation; and episodes of glacial advance and retreat mean that the sediment flux has been very uneven. As a result of these changing factors the rate of growth of the deltas must have altered significantly over time. It is probable that, as the climate warmed and vegetation cover increased, the glacial andperiglacial sediment supply decreased. In the early stages of the formation of each delta, rapid down-cutting of the unconsolidated sediment of the preceding delta produced abundant sediment and a fast growth rate. The growth rate would have slowed over time as the surface \u00e1rea expanded and the front of the delta lengthened. Growth also slowed significantly as the height of the foresets increased as the delta built out into deeper water.

It is probable that the deltas started forming about 13,000 years before the present and that delta number 2 had built out by about 8,500 years ago. Therefore deltas number 7 to number 2 formed over a period of about 5,000 years. By contrast the much smaller delta number 1 has formed since between 7,000 and 5,500 years ago. The small size of delta number 1 compared with deltas 2, 3 and 4 (Fig. 4) therefore indicates a significant slowing in the rate of formation.

It is estimated, on the basis of its size and age, that the presently active delta of the Las Dunas River is prograding slowly, at less than 0.2 m and possibly as little as 0.1 m per year. This is comparable to the 0.4 m per year determined for the Alta Delta of Norway (C\u00f3rner *et al.,* 1990).

12. Conclusions

Thick successions of gravel-dominated sediment form distinctive facies on lacustrine braid deltas in southern Chile. The deltas can be divided into two morphological components, the delta fan and the beach embayment, each with characteristic facies.

The deltas are the produc\u00eds of a high sediment influx onto a steep shoreline. As it built out into the lake the expanding fan developed a wedge shape, thickening into the deeper water. The sedimentary successions therefore wedge in the opposite di-rection from those of tectonically controlled basin margins where fan growth keeps pace with basin subsidence.

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