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Environments of Tidal Marsh Deposition in Laguna San Rafael Area, Southern Chile

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ABSTRACT

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Surveys of tidal marshes associated with environments of glacial retreat, braided river channel migration, and earthquake-induced subsidence revealed variations in marsh topography and morphology. Profiles show changes in marsh elevation caused by variations in substrate conditions and depth. Types of marsh surface pan, characterized by the absence of vegetation and the retention of water at low tide, are found in all three marsh environments. Classic channel pans are found, as well as other pan morphologies related to local surface conditions. Pans may be either primary or secondary marsh surface features, but are found in all three types of marsh.

ADDITIONAL INDEX WORDS: *tidal marsh, salt pan, sedimentation, braided rivers, subsidence, Laguna San Rafael, Chile.*

INTRODUCTION

The dynamic nature of the coast of southern Chile is reflected in its fast-evolving landscape. Tectonic activity related to the triple junction where the Nazca, Antarctica and South American crustal plates meet, just offshore of the Taitao Peninsula (Figure 1a), produces massive earthquakes and rapid crustal deformation. The coastline is dominated by the steep fault-controlled margin of the Andes which rises to over 1400 m from sea level in less than 5 kilometers. The high rainfall in the area, measured at over 4000 mm per year at the Laguna San Rafael (ENOMOTO and NAKAJIMA, 1985), provides rapid snow accumulation in the ice-fields. The San Rafael Glacier, an outlet glacier from the North Patagonian Icefield, reaches sea level and calves into a tidal lagoon. The glacier, classified by LLIBOUTRY (1956) as the fifth largest in Chile, flows at rates of up to 17 m per day (NAKAJIMA, 1985) and produces icebergs on the Laguna San Rafael (Figure 1b). Occasionally these are swept out of the Laguna with the tide through the Rio Tempanos and may reach the Golfo Elefantes before melting. The Rio Tempanos is the only outlet of the Laguna San Rafael and passage through this channel reduces the tidal range from 3 m on springs in the Golfo Elefantes to 1.6 m on the north shore of the Laguna.

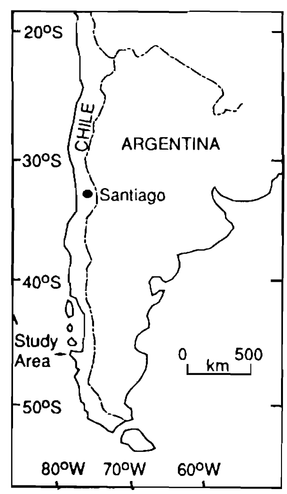

Figure 1a. Location of study area.

Although these environmental factors cause rapid landscape change in the area, previous scientific work in the area has not focused on these issues. Exploration in the area has attempted reconstruction of Late Pleistocene environments (American Geographical Society Southern Chile Expedition 1959, as reported by

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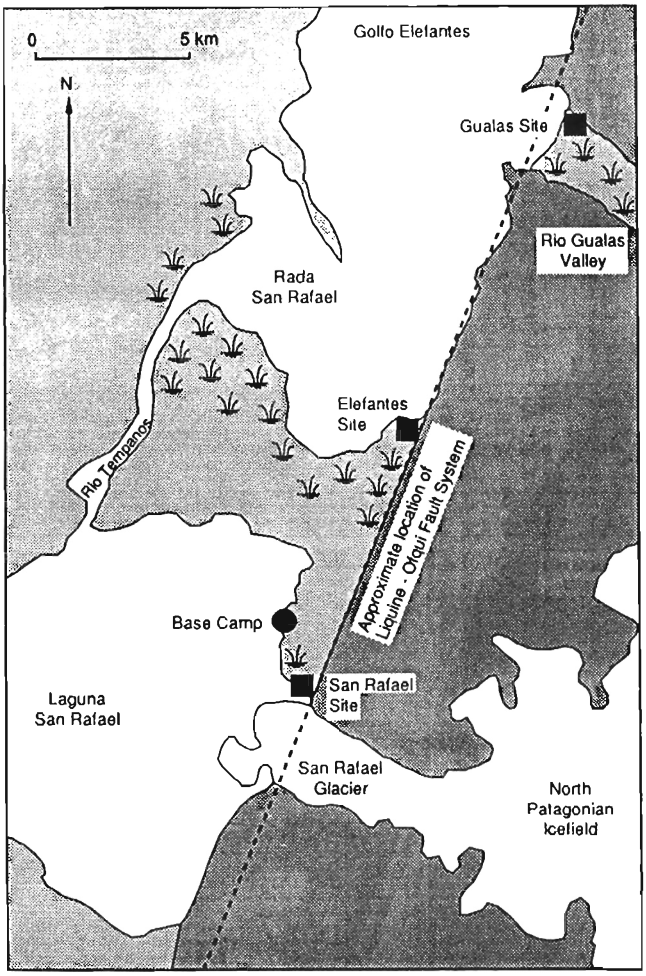

Figure 1b. Map of Laguna San Rafael and tidal marsh study sites.

HEUSSER, 1960), examined the meteorology and glaciology of the area as indicative of climatic change (Japanese Glaciological Research Project on Patagonia (GRPP) 1983-84 and 1986-87, as reported by NAKAJIMA, 1985), and undertaken geological mapping of the region (HERRON *et al.*, 1981; NIEMEYER *et al.*, 1984; FORSYTHE and NELSON, 1985). An Operation Raleigh expedition in 1986 broadened this scope of work into neotectonics, braided stream development and tidal dynamics (REED *et al.*, 1988). This study aimed to further these geomorphological investigations and examine the various types of tidal marsh deposit found on the coast in the vicinity of the Laguna San Rafael. Marshes of the area are variously influenced by glacial meltwater, river channel migration and major subsidence events associated with earthquakes and fault movements. This study aims to compare and contrast tidal marshes subjected to these factors in terms of their morphology and development. Three particular marsh environments were identified:

(1) marshes on the south side of Rada San Rafael, flooded by tidal waters from the Golfo Elefantes (ELEFANTES);

(2) marshes in the estuary of the Rio Gualas, a braided stream fed by glacial meltwater (GUALAS);

(3) initial marsh development between

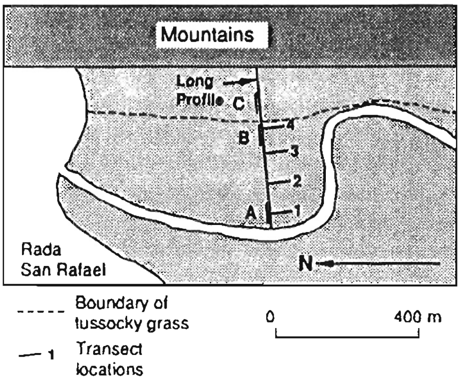

Figure 2. Sketch map of Elefantes study site.

moraine and outwash ridges adjacent to the terminus of the San Rafael Glacier (SAN RAFAEL).

STUDY AREAS

Elefantes

This is a small marsh, extending approximately 500 m from the base of the mountains, in a meander bend of a large tidal creek (Figure 2). It is part of an extensive marsh area extending from the steep margin of the Andes in the east to the Rio Tempanos in the west (Figure 1). The neotectonic history of this area has been described using dendrochronology and historical records (REED *et al.*, 1988). They suggest that a major event occurred in the 1830's, associated with the 1837 earthquake, causing 2–2.5 m of subsidence in the area of the Elefantes site. Marsh sediments have accumulated over a horizon of dead trees, killed by submergence after the subsidence event. The tidal range in this area is 2.5–3 m on springs.

Gualas

In its lower reaches the Gualas valley becomes an estuary, the interchannel bars of the river being flooded at high tide. On many of the bars, and in areas between the river and the steep valley wall, fine sediments have accumulated over the sand and gravel channel deposits. In these areas marsh vegetation has become established. The study marsh is adjacent to the northern valley side, extending approximately 120 m from the valley side and 300 m in length.

San Rafael

As the San Rafael Glacier retreats from the Laguna, moraines and outwash deposits on the lowlying area to the north of the glacier are exposed. Recent retreat has revealed a series of sub-parallel boulder ridges approximately 1 m high and 5–10 m apart. These are in the intertidal zone and depressions between the ridges are flooded at high tide. Fine sediments have begun to accumulate in the depressions over the sand and boulders, vegetation is beginning to colonize and marsh forms are developing.

METHODS

Morphology of marshes at Elefantes and Gualas was surveyed by levelling, and elevations related to water level at the time of survey. An attempt has been made to standardize these elevations, no existing benchmark system being available and sites being too far apart to establish a temporary system, by relating water levels to mean sealevel in Laguna San Rafael. Estimates of tidal changes between sites, both in time and elevation, are based on tidal data collected during studies of the Rio Tempanos in 1986 (REED, 1988) and during the present study. Both generalized profiles of the whole marsh and more detailed short sections, were surveyed to characterize both marsh surface morphology and the topography of the creeks and salt pans. At San Rafael such surveying was not possible. Pits were dug through the marsh sediments at all three sites to reveal the depth of sedimentation above the base horizon.

At all sites the dimensions of unvegetated marsh surface depressions or 'pans' were measured. Marsh pans were defined as bare areas on the marsh surface, filled with water at high tide and almost entirely surrounded by vegetated marsh. At Elefantes and Gualas, an attempt was made to classify pans according to their morphology, in particular identifying those which may have been formed by the collapse of channel banks, usually termed 'channel pans' (YAPP and JOHNS, 1917). At these sites all pans within certain areas of the marsh were measured, and at Elefantes additional transects across the marsh were taken along which all surface depressions, channels or pans, were measured. Such dimensional survey was limited at San Rafael but long axis, short axis and depth were measured on a sample of pans.

RESULTS

Elefantes

At Elefantes, a generalized long profile across the marsh surface was surveyed with three shorter sections of the profile being surveyed in detail (Figure 2). The long profile (Figure 3) shows variations in the elevation of the marsh surface close to the main marsh channel and adjacent to the base of the mountains. Near to the western margin of the marsh, bordered by the tidal creek, the marsh is highly dissected as shown on Profile A (Figure 3). Although the long profile was surveyed on the vegetated marsh surface only, there are many irregularities in the shape of the marsh profile in this zone. Towards the mountains, there is an increase in elevation of the marsh surface of approximately 25 cm, before a depression associated with the topography of the fault zone further described in REED *et al.* (1988). The rise is associated with a change from the very low green marsh vegetation to tussocky grasses, almost 1 m high in places (Figure 2). Observa-

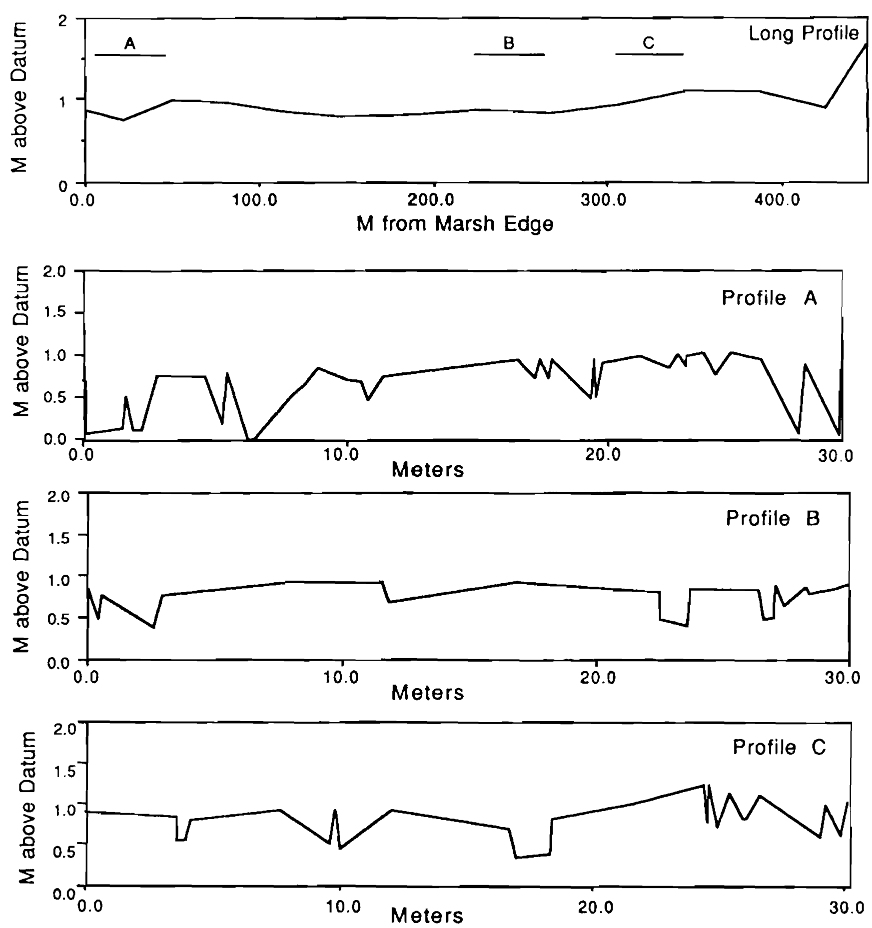

Figure 3. Long profile and detailed profiles across Elefantes marsh. See Figure 2 for profile locations.

tions also indicate that the grassy zone contains many fallen trees at or near the marsh surface, the numbers of which decline markedly into the zone of low marsh surface vegetation.

The detailed profiles show changes in the character of marsh topography across the two marsh zones. Close to the edge of the marsh at Profile A, the marsh is highly dissected by major runnels that drain directly into the main tidal creek. There is highly irregular surface topography in this area. At Profile B, close to the margin between the two marsh zones, the surface is more even with a few well defined pan features. Profile C, which crosses part of the tussocky grass marsh, has many fallen trees on the marsh surface and there are many small channels and pans in the complex marsh topography.

Further investigation of these changes in surface topography across the low marsh zone was attempted by measuring the dimensions of all surface depressions encountered along transects across the marsh perpendicular to the direction of the surveyed profiles (Transects 1–4 on Figure 2). The width, along the transect line, and depth of each feature was measured, and features were classified as follows:

(1) Channels — showing some connection with the active drainage network;

(2) Surface Pans — depressions on the marsh surface totally enclosed by vegetated marsh;

(3) Channel Pans — depressions on the marsh surface, enclosed by vegetated marsh but showing areal patterns similar to surrounding drainage network.

The results of this survey of marsh surface depressions is shown in Table 1. In addition, a survey of all pans in a 30 m × 30 m area of the low marsh surface was undertaken. Within this area all pans were measured for their long and short axis and depth. No attempt was made to classify the pans. The results of this areal sample of 50 pans are shown in Table 2.

Gualas

Both detailed cross and long profiles were surveyed on the study marsh in the Rio Gualas estuary (Figure 4). All the long profiles (A-D) (Figure 5) show a gradual decline in elevation from the back of the marsh towards the river, but with a steep drop or cliff into the river channel. Profile B includes an area of beach at the back of the marsh and its steep gradient down to the marsh surface proper. The marsh elevation shown on Profile B is also markedly higher than in the other long profiles, reflecting the increase in elevation in the centre of the marsh clearly shown on the cross profile. This corresponds to the area in front of the 'beach' and may be due to a change in substrate conditions. The most prominent surface topography, including creeks and pans, is shown on the profiles. A census of surface pans was conducted for the area from the western margin of the marsh up to Profile C. Because of the proximity of the steeply cliffed valley side, much of the eastern portion of the marsh was strewn with rocks and boulders, together with debris from the river including logs. For each pan long and short axis and depth was measured and pans classified as follows:

(1) Surface Pans — depressions on the marsh surface totally enclosed by vegetated marsh;

(2) Channel Pans — depressions on the marsh surface, enclosed by vegetated marsh but showing patterns similar to surrounding drainage network;

(3) Feeder Pans — depressions which are almost totally enclosed by marsh but which have a shallow 'feeder' connection with an adjacent channel;

(4) Obstacle Pans — those pans which include an obstacle to flow *e.g.* a log or rock.

A total of 105 pans were measured and the results of the census are shown in Table 2.

San Rafael

No surface topographic survey was possible at this location. Marsh vegetation was beginning to colonize the low inter-tidal depressions between the bouldery ridges of moraine and outwash material. Initially the grass colonizes individual pebbles or small boulders and gradually amalgamates into a continuous cover (Figure 6) with isolated clumps of taller grass. The centres of depressions often remain full of water at low tide and appear as broad shallow pans with long axes parallel to the boulder ridges (Figure 7). There is little creek or channel development and on the flood tide whole depressions act as channels, the ridges controlling the pattern of flooding. A clear boundary exists between the vegetated zone where fine

Table 1. *Results of transect study of marsh surface pans at Elefantes. For location of transects see Figure 2.*

	Width	Depth	W/D	n
Transect 1				
Channels	0.343	0.308	1.1	4
Surface Pans	1.078	0.313	3.28	4
Channel Pans	0.734	0.346	2.22	5
Mean	0.718	0.322		
Transect 2				
Channels	0.702	0.526	1.325	25
Surface Pans	0.669	0.275	2.49	19
Channel Pans	1.052	0.345	2.9	12
Mean	0.808	0.382		
Transect 3				
Channels	0.649	0.487	1.39	17
Surface Pans	1.268	0.275	4.95	11
Channel Pans	0.871	0.287	3.18	7
Mean	0.929	0.350		
Transect 4				
Channels	0.781	0.66	1.2	8
Surface Pans	0.888	0.318	2.73	11
Channel Pans	0.825	0.343	2.9	6
Mean	0.831	0.440		

Table 2. *Results of pan surveys at each study site.*

	Mean Length (m)	Mean Width (m)	Mean Depth (m)	Length/Width	Length/Depth
Elefantes					
Areal Sample (n = 50)	0.959	0.528	0.157	1.943	6.9
Transects–					
surface pans (45)	0.905	N/A	0.29	N/A	3.221
channel pans (30)	0.911	N/A	0.331	N/A	2.847
Gualas					
Total Sample (n = 105)	1.958	0.615	0.091	5.084	25.291
with obstacle (33)	2.023	0.648	0.113	5.902	22.763
feeder pans (15)	2.224	0.695	0.086	4.838	26.857
channel pans (7)	5.271	0.433	0.089	15.602	62.387
surface pans (50)	1.371	0.595	0.079	3.145	21.296
San Rafael					
Total Sample (n = 12)	12.02	3.59	0.096	3.343	122.88
depression pans (7)	17.27	4.71	0.093	4.173	172.22
local pans (5)	4.66	2.02	0.100	2.181	53.818

sediment has been deposited, and the exposed boulder ridges.

In addition to the broad, shallow depression pans, isolated smaller pan forms were found in locations not directly controlled by the pattern of ridges (Figure 6). Length, width and depth measurements were taken of samples of both the smaller "local" pans and the larger "depression" pans. The results are shown in Table 2.

DISCUSSION

Marsh Topography

The results of the topographic survey at Elefantes indicate a division of the marsh into two zones, with approximately 25 cm difference in height. The profile is similar to that found in many salt marshes in North America and

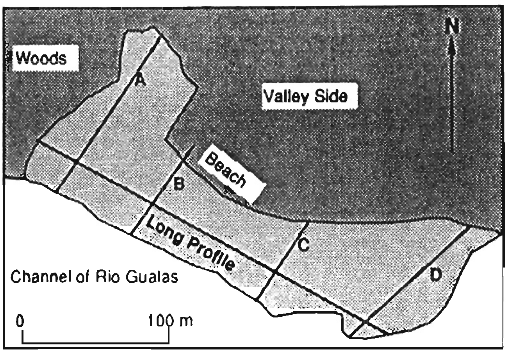

Figure 4. Sketch map of Gualas study site.

northwest Europe where high marsh and low marsh zones are common (RANWELL, 1972; FREY and BASAN, 1985). At Elefantes the transition is marked by a change from low vegetation to tall grasses, caused by changing flooding and drainage characteristics, and a decrease in fallen tree debris on the low marsh surface. The transect study does not extend into the high marsh zone and so cannot show any changes in marsh morphology. However, there is a suggestion that towards the high marsh, *i.e.* on transect 4, there is an increase in channel depth, while channel and surface pan depth remains fairly constant (Table 1).

A pit dug through the marsh sediments on the low marsh, close to the main tidal creek, revealed a clear horizon of root and branch tree debris at approximately 1 m below the surface. The sediments deposited onto top of this horizon showed no clear banding or zonation, suggesting continuous deposition above the surface. Where fallen tree debris occurs on the marsh surface, in the high marsh and on the margins of the low marsh, some deposition has occurred atop the logs. However, this rarely exceeds 10 cm. Assuming that the tree debris is all related to the same subsidence event, the present marsh zonation and differences in sedimentation suggest that the low marsh has developed since the tree mortality while the high marsh was previously above the level of tidal flooding.

REED *et al.* (1988) suggest that the 1837 earthquake would have produced 2–2.5 m of subsidence in this area. Were this to be the case, what is presently the high marsh zone would have been above the level of tidal inundation and an area of tree growth. Subsidence caused inundation and salinity stress to the trees, resulting in the death and the fallen logs common in the high marsh. Adjacent to this, and bordering on the Rada San Rafael was a lower-lying area, also covered with trees, original elevational differences possibly being related to previous subsidence events or river/tidal channel migration. When this lower area subsided it became intertidal and sediments began to accumulate above the fallen tree debris. Assuming the subsidence was related to the 1837 earthquake, the average sedimentation rate in the marsh has been approximately 0.7 cm/yr, the same magnitude as that in marshes in the United States currently subjected to relative sea-level rise (STEVENSON *et al.*, 1986). However, given that the subsidence event produced a sudden increase in water level, rather than the gradual change associated with relative sea-level rise, the initial sedimentation rate would have been rapid because of the high frequency and depth of inundation. Therefore, present sedimentation rates are thought to be much less than 0.67 cm/yr on the low marsh, although no direct measurements are available. Radio isotope dating of the sediments using ^{210}Pb (ARMENTANO and WOODWELL, 1975; SHARMA *et al.*, 1987) would provide clarification of the age of the marsh sediments and changes in the sedimentation rate since 1837.

Marsh topography in the marshes bordering the Rio Gualas may be influenced by substrate conditions. The broad rise in elevation in the center of the marsh shown in the cross profile, and the high back margin of the marsh on Profile B where the marsh is backed by a gravel beach. Pits dug through the marsh sediments showed that the marsh was deposited directly upon gravel or sandy sediments overlying gravel. Such a vertical profile is similar to that described by REED *et al.* (1988) in their study of braided barforms of the Rio Gualas. As the fine sediments and plant colonization composing the marsh are found atop channel bars, general marsh topography will be strongly influenced by bar shape and form.

Topography of the embryonic San Rafael marshes is strongly controlled by the landscape of bouldery ridges. As vegetation is only beginning to take hold, individual pebbles can still be recognized beneath the thin marsh soil. The

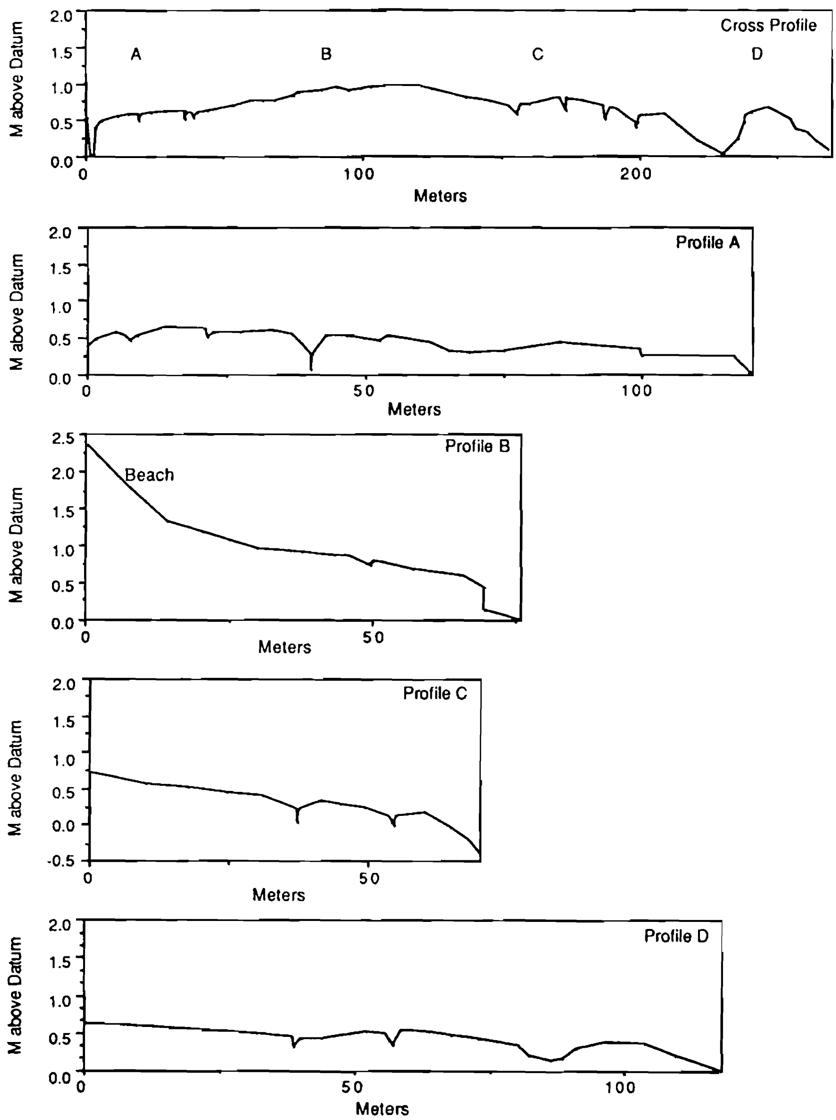

Figure 5. Cross profile and long profiles across Gualas marsh. See Figure 4 for profile locations.

morainic ridges of larger boulders control the pattern of tidal flooding, therefore influencing the location of fine sediment accumulation and the form of the marsh (Figures 6 and 7).

Marsh Surface Morphology

The surveys of marsh pans in the three study areas provide a total sample of 242 pans. Although the measurement of length is slightly different on the transact surveys at Elefantes, length being taken as the dimension of the pan where the transect crossed it, the measurement of depth is consistent at all locations. Comparing the areal survey measurements at Elefantes with the total survey of pans at Gualas shows a change in mean pan depth from 0.157 m to 0.091 m. The pans at Elefantes are significantly deeper than those at Gualas (t-test, $p = 0.05$), while there is no significant difference

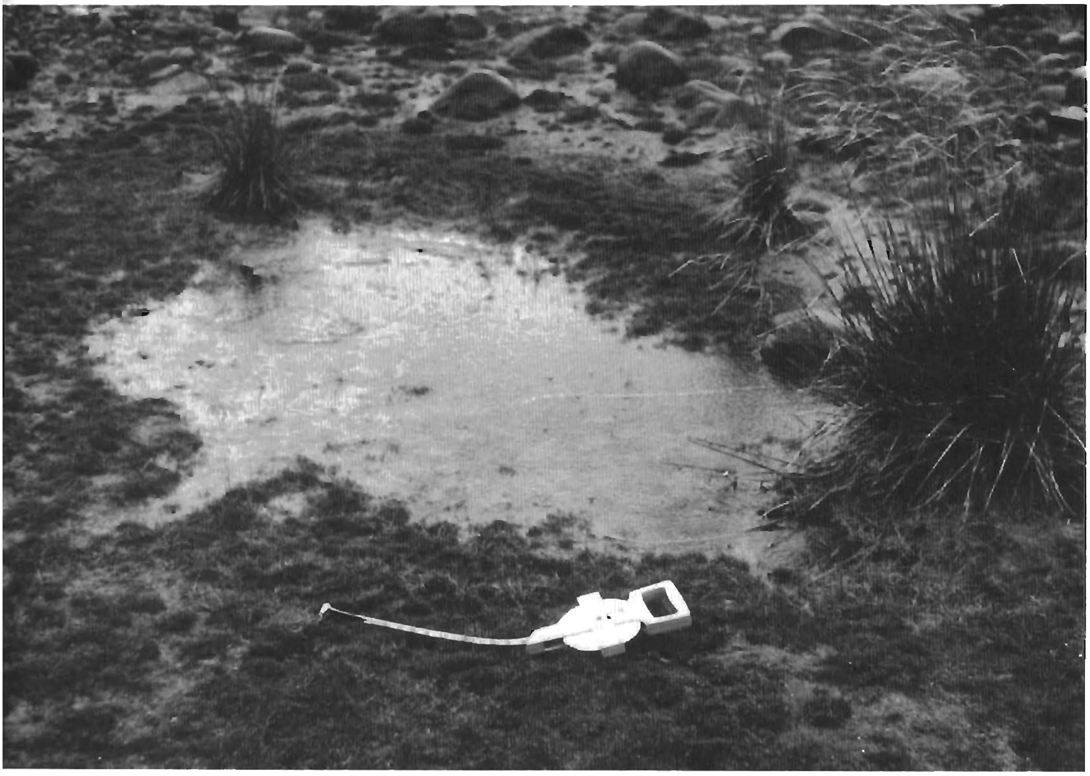

Figure 6. Marsh vegetation cover surrounding a small 'local' pan at San Rafael study site.

between the mean depth at Gualas and San Rafael, 0.091 m vs 0.096 m. This correspondence between measurements from the two recently glacially influenced sites, as opposed to the open coastal location of Elefantes, reflects the differences in marsh development between the areas. It has already been established that a considerable depth of sediment (>1 m) exists at Elefantes, and the marsh has probably developed over the last 150 years. In contrast, at Gualas the depth of marsh sediment varies between 18 cm at the back of the marsh, and 30 cm close to the Rio Gualas. At the back of the marsh, silts lie directly upon coarse gravel of the interchannel bar deposits, while where the sediment is deeper, the silts overlie sandy sediments with boulders at 50 cm below the surface. Similarly at San Rafael, fine sediment deposits are 5–10 cm deep and directly overlie pebbles and boulders of the glacial deposits.

This limited vertical development of the marsh controls the depth of marsh pans. There is considerable discussion on the development of salt marsh pans in marshes in north-west Europe (YAPP and JOHNS, 1917; PETHICK, 1974; BUTLER *et al.*, 1981) and whether they are primary forms, *i.e.* they develop at the same time as the vegetated marsh surface as areas which are not colonized, or secondary forms, *i.e.* they develop at some later stage when the marsh surface deteriorates for some reason. Observation at San Rafael, and the shallow nature of the marsh deposits, suggests that these pans are primary, and are developing in low areas where marsh vegetation is not colonising. The control of the depth of sediment on pan depth is shown by comparing the dimensions of depressions and local pans. Although there is no significant difference in depth (0.093 m vs 0.10 m), the depressions are significantly longer (t-test, $p = 0.10$), mean of 17.271 m, than the local pans, mean of 4.66 m. It is suggested that the smaller local pans may be formed when small icebergs are stranded on the marsh after

Figure 7. View of San Rafael study site showing depression pans between bouldery ridges of glacial debris. Note the small icebergs stranded on the marsh area and the snout of the San Rafael Glacier in the background.

high tide (Figure 7). Scouring by bergs when partially afloat may account for the slightly increased depth of these local pans. Thus, the pan forms at San Rafael, even though the marsh is only in its initial stages of development, may be either primary or secondary.

Data concerning the different types of pans identified at both Elefantes and Gualas allow further examination of the primary or secondary nature of pans. Channel pans, recognized by YAPP and JOHNS (1917), are secondary pans which develop when a section of a marsh creek becomes isolated from the drainage network, usually by collapse of the channel banks. The resulting pan retains the plan form of part of the channel network, but remains hydrologically isolated except during overmarsh tides. At Elefantes channel pans were distinguished by their planform and they do not show any significant differences in depth or length from other surface pans. However, at Gualas, where the same visual distinction was made, the channel pans have a mean length at least twice that of other pans and are also narrower. They only represent 6.7% of the total pans surveyed at Gualas; and so, although rare, it appears that classic channel pans are present.

A distinction was also made at Gualas between surface pan features with and without obstacles to flow. These obstacles were either driftwood logs, beached on the marsh during high river/tidal flows, or rocks fallen from a steep cliff close to the valley wall. These pans ('with obstacles' in Table 2) are significantly deeper (t-test, $p = 0.05$) than the other surface pans, 0.113 m vs 0.079 m, while there is no significant difference in depth between surface and channel or feeder pans. One of the mechanisms maintaining marsh pans and preventing their colonisation by vegetation, is eddy action in the pan during overmarsh tides. The logs or rocks, either in the pan or on the margins, will increase this eddying by obstructing water flow into the pan and so preventing accretion on the pan bed. The feeder pans identified at Gualas do not show any different dimensions from other surface pans. They are visually distinct with shallow, vegetated channels connecting them with adjacent creeks. This is very similar to one stage in the development of a 'keyhole' pan (BUTLER *et al.*, 1981) but the evolutionary sequence identified by Butler *et al.* at Colne Point, eastern England, is not present in the Rio Gualas marshes.

CONCLUSIONS

The measurements of marsh surface topography and morphology presented here provide some insight into the processes contributing to tidal marsh development in the vicinity of Laguna San Rafael. There are distinct morphological differences between the marshes developed on glacial outwash and river deposits, and those formed after a major subsidence event. It seems clear that many of the surface pans at Gualas and San Rafael are primary features, developing with the marsh as vegetation colonises a bare surface. Those at Elefantes are more difficult to explain. Where the marsh sediments are 1 m deep and the pans only reach to 30 cm, this suggests that either the pans are secondary features and holes have appeared in the marsh, or the pan bed accretes with the marsh surface and there is some equilibrium depth for the pans. Further studies of pan dynamics would be required to resolve this problem.

That pans are equilibrium forms is also suggested by the regularity of dimensions of the different surface pan types at Gualas. With the exception of the channel pans, a clear dimensional category on their own, there is very little variation in pan shape. The importance of disruptions to equilibrium process-response are indicated by the change in depth, if not width and length, shown in the pans containing some obstacle to flow. Again, a morphological study cannot elucidate the processes controlling marsh pan formation, but the results presented here have shown clear similarities in form between marshes developing in contrasting environments. Further studies of hydrology and sediment dynamics in this area would greatly enhance our understanding of the morphology of these tidal marshes.

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