EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION
VOLUME 84 NUMBER 1
7 JANUARY 2003
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New Mechanisms Studied for Creek Formation in Tidal Flats: From Crabs to Tidal Channels

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Mechanisms for the formation of creeks in tidal flats are rarely discussed in the peer-reviewed literature. Moreover, while there are general theories about how creeks form in tidal flats, there is no data to support these theories. It is generally believed that marshes inherit creeks from previous tidal flats that plants colonize, and that further modify the creeks. Recently, we have discovered new mechanisms for creek formation in three different environments of Argentina in which tidal creeks are actually originating in both fresh and salt marshes. One of the most surprising and interesting findings is that creek formation can actually be a product of the intense action of crabs (*Chasmagnatus granulata*). In these settings, crabs first interact with a halophytic plant (*Salicornia ambigua*), developing zones of high-density of crab holes, which then are utilized by groundwater and tidal action to form channels. This specific interaction forms a series of rings that, to the best of our knowledge, have not been described elsewhere in the literature.

In this article, we examine the advances made by an interdisciplinary project working at a recently discovered site within the Bahía Blanca Estuary (Figure 1). The project involves researchers and Ph.D. students from diverse disciplines, including oceanographers, biologists, chemists, engineers, and geographers tackling the variety of problems centered on channel formation, but also covering aspects of soil mechanics, turbulence processes, sediment and nutrient transport, phyto- and zooplankton, benthic communities, and air-sea-land interaction processes, to name a few.

Bioengineering or ecosystem engineering is common in many of Earth's environments, but what makes this site unique is the development of the *Salicornia* rings circling a center area full of crab holes (Figure 2a). *Salicornia ambigua* is a bi-annual halophyte marsh plant that inhabits a region of about 0.5 to 1 m below the highest astronomic tide, an area flooded only on spring tides. The site was discovered by O. Iribarne in the summer of 1999–2000 and since then, we have developed a couple of 3-year research projects to try to understand the complete cycle, from the initial plant-crab interaction, to the formation and further evolution of the channels.

Saliconia Rings and Formation of Tidal Channels

When analyzing the spatial distribution of *Salicornia*, *Iribarne et al.* [2002] found that the plants were mostly distributed in circles of up to 1.5–8 m in diameter, with the plants concentrated in a ring along the outer portion of the circle (Figure 2a). These rings vary in width from 0.5 to 1.5 m. The central part of the circle is an unvegetated salt pan, but it is densely excavated by the burrowing crab *Chasmagnathus granulata*. Hole density reaches from 40 to 60 holes per m^2. The holes made by the crabs have a diameter of up to 12 cm, and they reach up to 70–100 cm into the sediment [*Iribarne et al.*, 1997; *Bortolus and Iribarne*, 1999]. By repeated surveying of the area (surveys are made approximately every 15 days), we have been able to deduce the mechanism for salt pan formation.

In the studied salt marsh, *Salicornia* forms originally a relatively small, ellipsoidal mat about 0.20–0.50 m in its long diameter and a 0.15–0.30-m minor axis. As the plant grows, the sediments underneath maintain higher humidity and decrease their hardness. *Salicornia* provides shade (a special experiment is being done to test this issue) for the crabs that dig a hole just under the plants [*Bortolus et al.*, 2002]. Crabs take advantage of these characteristics and construct burrows in these sites. Their activities are thus facilitated by the presence of the plant. Once crab burrows are established, their sediment removal affects the stability of the plants. *Salicornia* then starts growing away from the center as plants die at the center area, leaving this area with a burrowing crab bed. We observed a growing process of the circle, as if the increase in the crab population in the center had produced an outward plant migration. Increments in size allow for the merging of adjacent circles, which at first attain a "figure 8" configuration; and after further merging, they tend to reach different configurations (Figure 2b).

One of the effects of the crabs, besides removing the sediment, is the homogenization

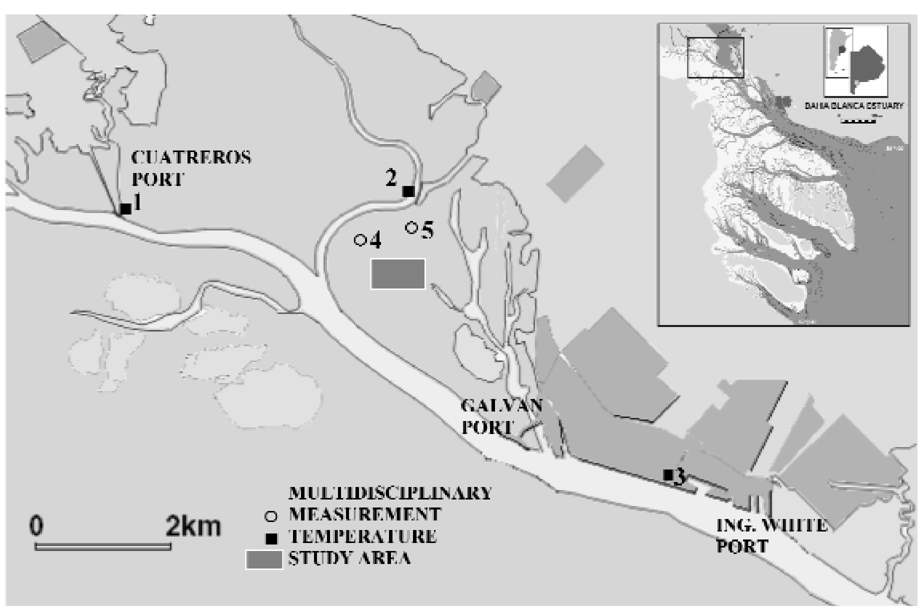

Fig. 1. Location of the study area in the Bahía Blanca Estuary, Argentina.

of the sediment layers [*Botto et al.*, 2000], including their salinity. Surface salinity on bare sediments is higher (57) than inside the *Salicornia* patches without crabs (43), and both are much higher than in areas inhabited by *Salicornia* and crabs, or in the crab bed in the inner part of the *Salicornia* rings (23–24). Salinity below the 10 cm depth showed much lower differences (25–37). This may be one of the reasons why *S. ambigua* has this concentric growth pattern. Furthermore, preliminary observations have been made which show that *Salicornia* affected by crabs increases its sexual reproduction from the center of the rings outward, which is a common response of clonal species to disturbance.

Those circles located on the lower marsh are frequently inundated. Water discharges follow minor changes in the slope of the terrain, and so differential erosion occurs during the ebb. Crab holes in the salt pan convert the soil into a sort of "soft Swiss cheese," significantly reducing soil compaction and consistency. The fact that the crab holes are permanently inundated produces two effects. First, silty clay sediments—characteristic of this area—become partly loose; and second, the water in the holes starts to migrate, breaking intercave walls and developing a groundwater stream that undermines soil. Under the pan surface, caves are formed where groundwater flows can be seen. A further stage in the development of the channel appears when soil surface fails. At this stage, the channel has only a general structure filled with remnants of intercave walls (Figure 2b), around which water circulates [*Perillo and Iribarne*, 2002]. The final stage is reached when the walls are eroded after a number of tides and the channel presents smooth, low-slope banks. Crabs can be found along the channel banks, but no plants are observed. As a result, along the channels, the original tidal flat is moving landward at the expense of the salt marsh.

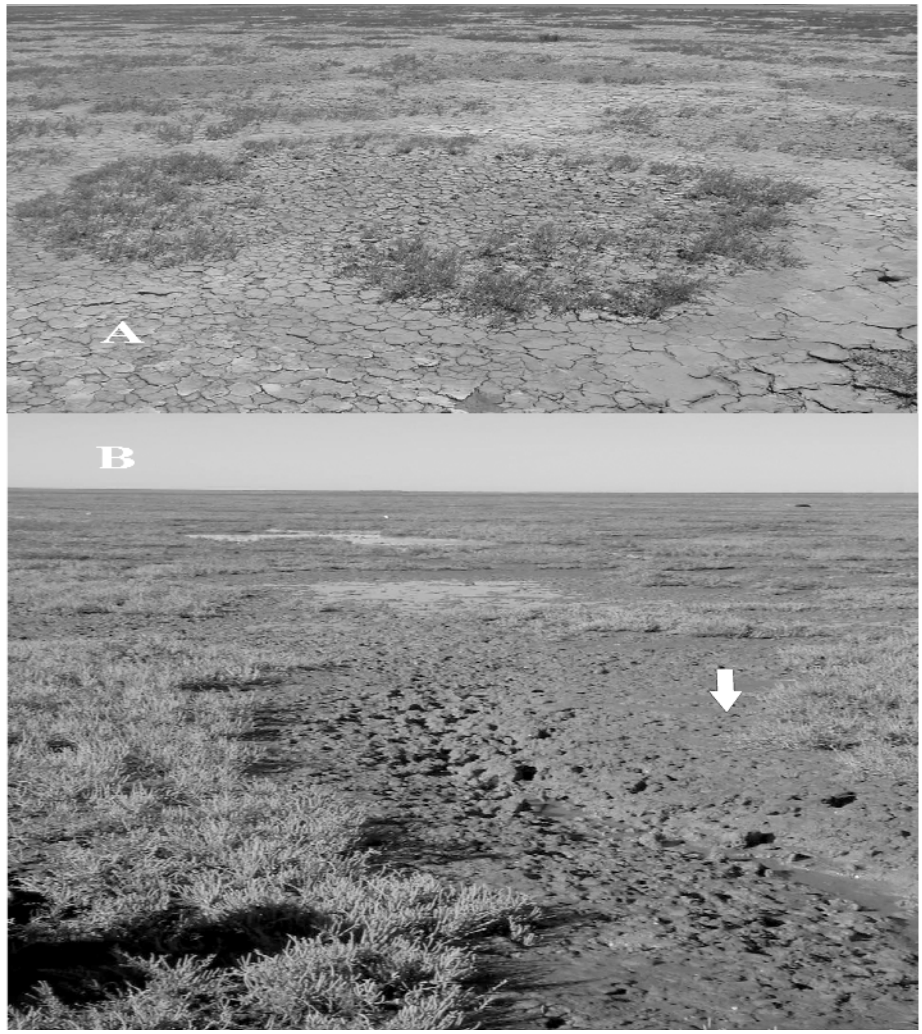

Fig. 2. Example of (a) typical Salicornia *circle and (b) a tidal channel formed by the process described in the text. In the upper central portion of the lower photo, a couple of inundated circles indicates the continuity of the channel system. The arrow points to the soil crusts.*

Channels may further migrate inland by headward erosion. However, we did not observe any channel head that crossed an outer *Salicornia* ring. The formation of these channels rapidly induces development of tributaries that reach the main channel from outside the ring. Recent estimates for some channels, suggests that landward migration is on the order of 0.10–0.20 m per day (Figure 3a). We also observed that channel migration accelerates during spring and summer and is reduced during fall and winter coincident with the variations in crab activity. However, the length of this data series (a little over a year) still is not long enough to provide conclusive estimations.

Another interesting feature observed in this marsh is the presence of slabs of very compacted (marked with an arrow in Figure 2b), high salinity (up to 91) silts. These unvegetated slabs are more common on the lower marsh near the channels. Although their formation is still under study, it is evident that they have been part of previous salt pans, but unrelated to crabs. The importance of these slabs, in the context of the present study, is that they exert a control on lateral channel development. Furthermore, we observed a ring which was partly controlled by two slabs that also formed the flanks of the inlet between the ring and the main channel. Thus, channel development, especially lateral growth, is affected by the presence of the slabs. Due to the hard condition of the sediments, crabs do not make burrows in these slabs.

Experimental Studies

From the previous descriptions, it is obvious that understanding of the whole process, from plant inception to the formation and evolution of the tidal channels, requires an integrated approach. Multi- and interdisciplinary intensive studies in tidal flats have developed only recently. The first project was denominated LISP'89 [*Daborn*, 1991] and included over 30 researchers of many countries working simultaneously in a specific tidal flat of the Bay of Fundy. Since then, other LISP-based projects have been developed (i.e., LISP UK, INTRMUD) in Europe. Although we have fewer resources, our project at the Bahía Blanca Estuary is mapped along the same lines of the LISP criteria of integrated research.

At the present time, the project includes long-term monitoring of factors such as tides, waves, soil-water-air temperature, and meteorology. Every 15 days, field surveys are made with determination of groundwater levels; sediment erosion-accumulation series [*Perillo et al.*, 2002] (Figure 3a); channel form evolution and migration (Figure 3b) (using a mobile bridge that was designed exclusively for this study); ring size and characteristics; chemical (Figure 3c) and biological (Figure 3d), and physical characteristics; sampling of water (surficial and groundwater), plants, and sediments; and soil mechanics testing. As diatoms appear to be an important feature on the sediment erodability, sampling of surficial diatom distributions at the rings—both inside and outside—and other areas are also performed.

Every season, we are also conducting a two-day intensive experiment at two sites on the tidal flat/marsh complex. Both sites differ in the fact that one has a defined channel that is advancing, whereas the other has no channel at all. The study spans a whole spring tidal cycle, from low tide to the next one. As the tidal bore advances, turbulence and suspended sediment concentration at 10 Hz are measured with a Sontek ADV Field. Also, the bore is simultaneously sampled for biological, sedimentological, and chemical parameters.

At the end of the 3-year project, we expect to have a clear and quantitative idea of the full mechanism that covers crab inceptions, to the formation and evolution of the channels. We also hope to understand the conditions by which some channels are much deeper that adjacent ones, considering that surface topography is very smooth and tidal range is homogenous over the inter-tidal environment. Our interest also focuses on defining the criteria influencing channel equilibrium and preferences for crab and plant colonization, as well as differences in sedimentation and erosion processes observed over the area.

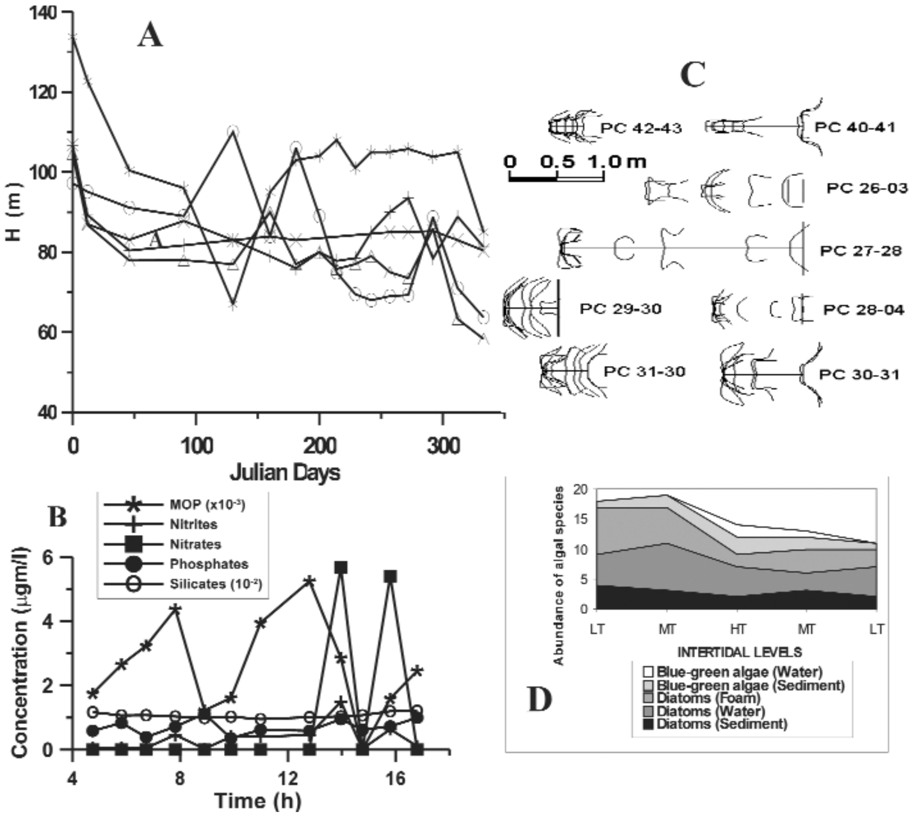

Fig. 3. Examples of time series data being collected in the study. (a) Sediment erosion accumulation rates estimated at 5 stations during almost one year demonstrating the large spatial variability observed in the area; (b) time and spatial evolution of 8 channel heads during almost one year; note that the head widens after the retreat; (c) plot of nutrients measured during an inundation period at station 4; (d) abundance of algal species in the water during an inundation period.

Acknowledgments

Project participants are Jorge Marcovecchio, Elisa Parodi, M. Cintia Piccolo, Dario Minkoff, Mauricio Escapa, Daniel E. Pérez, Jorge Gutierrez, Florencia Botto, Gabriela Palomo, and Pablo Riveiro. Support for these studies is provided by individual grants to the authors by the Fundación Antorchas.

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USGS Warns of increased Rain-induced Landslide Risks

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Heavy rains in mid-December have brought moisture levels in parts of the San Francisco Bay area to the point of soil saturation and the midst of a potential landslide season that could continue through March, according to the U.S. Geological Survey (USGS).

The 10-county Bay area is just one of a number of regions across the United States where rain-induced landslides are posing a serious, and often increasing, risk.

The U.S. National Academy of Sciences (NAS) currently is preparing a report on optimum strategies to mitigate landslide risks, which is expected to be released in the spring of 2003. A June 2002 academy report noted the need for a more aggressive national program to mitigate landslide hazards.

In spite of this, and at a time when USGS scientists say they are nearing the ability to experimentally forecast landslides, the agency charged with taking the lead on landslide hazard warnings is stumbling along with a lack of resources.

John Pallister, coordinator of the USGS Landslide Hazards Program, said that while risks from landslides are increasing due to continued development on hill slopes, research is moving forward to develop more rigorous models for landslide and rainfall-induced debris flow. The agency is close to having a forecast mode for landslides, and could forecast the hazard on an experimental basis in about five years, he said.

Pallister added that forecasts could go forward on an operational basis at a later point, given adequate funding for the agency.

The 2002 report prepared by the NAS responded to a USGS report to Congress in the year 2000 which indicated that full implementation of a national landslide hazards mitigation strategy within the USGS would require about $20 million annually, rather than the survey's Landslide Hazard Program's current annual budget of $2.6 million. The increased funding would allow expanded research, assessment, monitoring, and establishing a cooperative assessment and mapping program to increase state and local government efforts, according to USGS.

A Diffuse National Issue

Although landslides minimally cause $2–3 billion in direct losses in the United States, they are so distributed geographically and diffuse that many people do not realize that they are a significant natural hazard, Pallister said. Adding to this lack of awareness about landslide risks, there is no systematic national collection and distribution of landslide hazards information, and damages caused by them often are attributed to a related storm, earth-