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Late Quaternary Sedimentary Sequence in the Bahía Blanca Estuary, Argentina

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ABSTRACT

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The Quaternary sedimentary sequence in the inner area of the Bahía Blanca Estuary is analyzed. A very compact Pliocene-Pleistocene sandy silt-silty sand is the oldest sediment which forms a hard basement of great areal extent in all of the estuary's coast. The Holocene sediments unconformably overlie this basement. Fluvial estuarine fine sand that forms relict lenticular accumulations lies on the pre-Holocene basement in the deeper part of the study profile (24 m under mean sea level). Above this sediment, there is an estuarine marine facies composed of sandy sediments with different proportions of gravel and abundant shell fragments, deposited by the transgressive Holocene cycle. With the slow rise in sea level, an extensive tidal flat formed by clayey-sandy silt was deposited over the Holocene littoral sediments. This material is located between 16 m (in its deeper sector) and sea bottom of the main channel. In the present shoreline, those sediments are found up to 8 m above mean sea level which is evidence of the evolution during post glacial time of the coast line. Finally, the decrease of sea level originated a large coastal plain which is the main present characteristic of the Bahía Blanca Estuary.

ADDITIONAL INDEX WORDS: *Quaternary, sedimentary sequence, fluvial estuarine and estuarine marine facies, stratigraphy, Bahia Blanca, Argentina.*

INTRODUCTION

The study of coastal sedimentary units, their sedimentological characteristics and their lateral and vertical relationship provide a relatively complete historic geologic record of coastal changes. Along the entire Argentine shoreline, there are important and numerous geological evidences of sea level changes during the Quaternary. The prevailing environmental characteristics (geomorphology, petrology, climatology) determined different types of sediment, fossils and several geoforms created by transgressive-regressive processes.

The Bahía Blanca Estuary (Figure 1) is a mesotidal system (mean tidal range is 3 m). Its main channel, Principal, is 60 km in length and has an average depth of 10 m. Extensive low marshes and wide tidal flats, covered by a dense network of minor channels and creeks, characterize the geomorphology of all the area (Figure 1). Due to low fresh-water inflow ($\sim$20 m^3 s^{-1}), the Principal Channel behaves largely as a partly mixed estuary but with a strong tendency to be sectionally homogeneous (PERILLO *et al.*, in press). Average surface salinities range from 15‰ at the estuary head to 32‰ at the mouth (ARANGO *et al.*, 1985; PERILLO *et al.*, in press). Vertical salinity over the water depth may vary between 0 and 3‰. Circulation is governed by reversal tidal currents, with average maximum vertically integrated values of 1.2 and 1.05 ms^{-1} for ebb and flood conditions, respectively. The dominance of ebb over flood produces bedload sediment transport towards the mouth of the estuary (ALIOTTA and PERILLO, 1987).

Holocene marine deposits are found in the subsurface in places near the present shoreline (GONZÁLEZ *et al.*, 1983; ALIOTTA *et al.*, 1987; FARINATI and ALIOTTA, 1987; ALIOTTA and FARINATI, 1990; FARINATI *et al.*, 1992). Between 8 and 10 m above mean sea level, the last Holocene transgression produced a series of sand-shell ridges (GONZÁLEZ, 1984; FARINATI, 1985; ALIOTTA and FARINATI, 1990) which are subparallel to the shoreline (Figure 2).

Although much research has been done on the deposits situated above sea level in the Bahía Blanca Estuary, very little is known about the sedimentological characteristics of the marine facies below the sea bottom. Only NEDECO-ARCONSULT (1983), ALIOTTA *et al.* (1991) and ALIOTTA *et al.* (1992) have made some advances on this subject. The purpose of this report is to determine and analyze the sediments that form the subsurface of the Principal Channel in the inner area of the Bahía Blanca Estuary and establish their stratigraphic relationships and geological evolution.

METHODS

For the sedimentological characterization of the subsurface of the Principal Channel, twenty-five cores were analyzed

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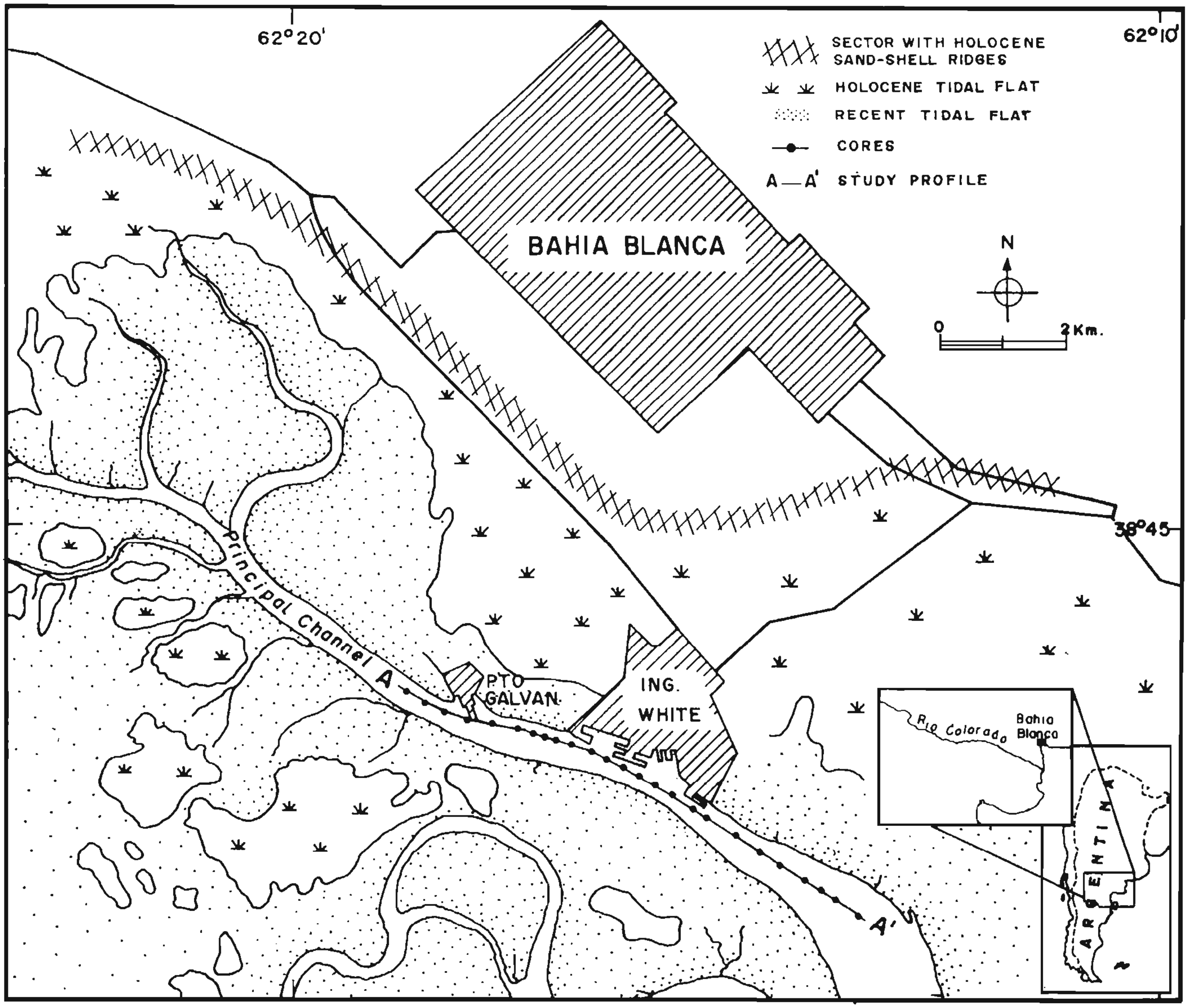

Figure 1. Bahía Blanca Estuary. Location of the study profile in the Principal Channel.

(Figure 1). They were obtained in the access of the channel at the Bahía Blanca harbor with a Rotary Universal Device and were referred to mean sea level (MSL). The length of the cores depended on the hardness of the material. The maximum penetration was reached at 20.40 m. The selection of samples was made on the basis of the macroscopic material characteristics. The coloration was determined as moist, in agreement with the Rock Colour Committee.

The samples belonging to compact levels were disaggregated with a solution of HCL (10%) and a sonic agitator. Sample texture was analyzed according to FOLK's (1974) procedure. For the granulometric analysis, an ATM sonic sifter with a 0.5 ϕ sieve interval was used. The fraction finer than 4 ϕ (silt + clay) was pipetted down to 8 ϕ. The data were statistically processed (FOLK and WARD, 1957) and the sediments were characterized following the scale of SHEPARD (1954).

The mineralogy of the sand (fraction 3.0 ϕ–3.5 ϕ) was identified by means of a petrologic microscope using mirbana essence as immersion fluid. The percentages of the major mineral species were obtained by counting a total of 200 grains. X-ray diffraction analyses were done, although the silt and clay fraction exceeded a total of 50%. The fossiliferous material was separated from the sediment after washing with peroxide and the determinations were carried out under a Carl Zeiss stereomicroscope.

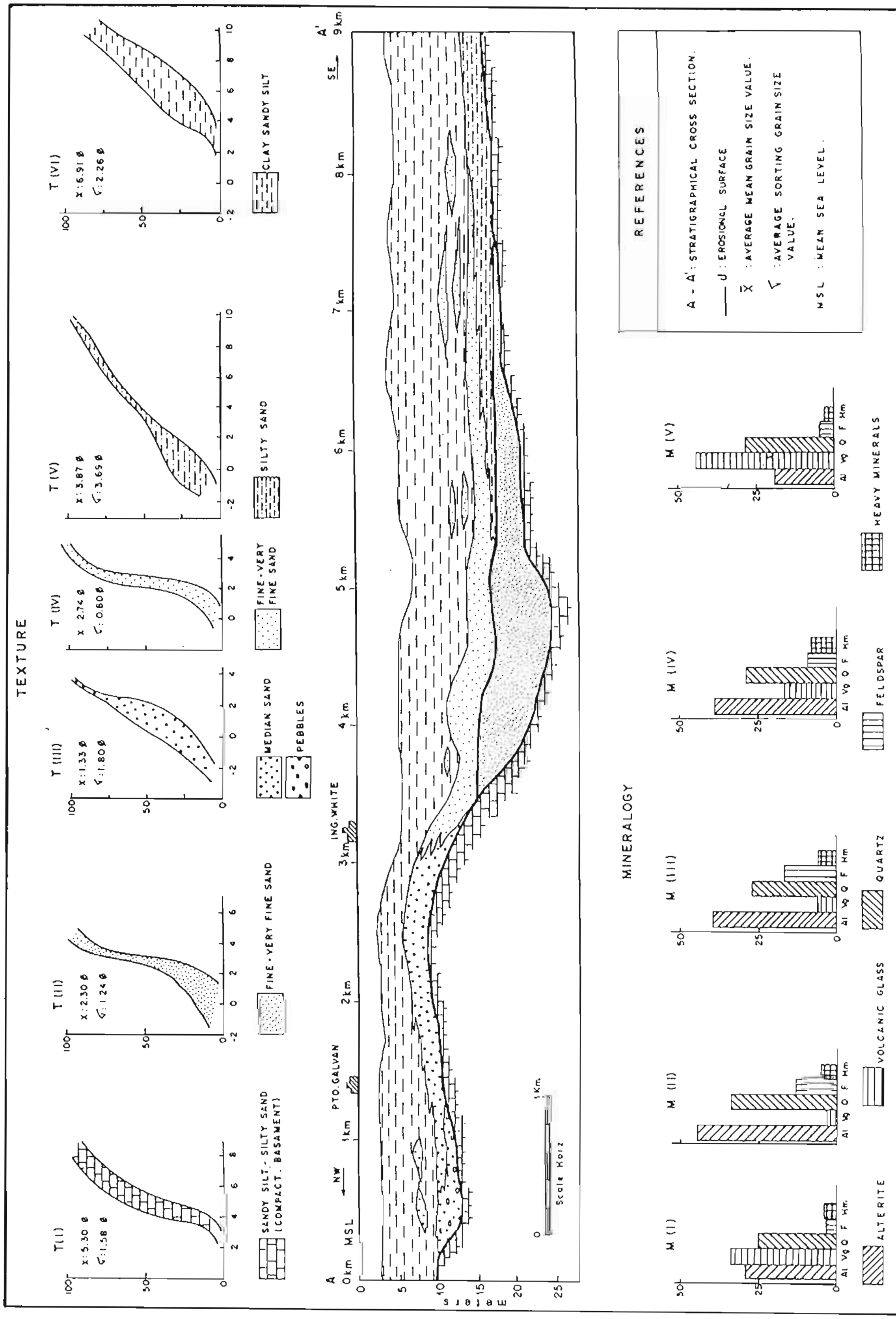

Figure 2. Stratigraphical cross section. Textures and mineralogical characteristics of the sediments.

RESULTS

A well lithified sandy silt-silty sand (colour 10YR 6/2 Pale Yellowish Brown), with a low proportion of clay (<15%), constitutes the oldest sediment in the analyzed cores. This material forms the basement of the Holocene sediments, which lie on an erosional surface found along the studied profile. This erosional surface cut into the pre-Holocene substratum has a concave configuration between km 3 and 9, approximately. It is steeper toward the northwest (0.40°) and towards the southeast it has a moderate slope (0.09°). The compact basement reaches its greatest depth at 24 m under MSL at km 4.7 (Figure 2).

The analyzed samples of the pre-Holocene facies have similar texture characteristics along the profile studied. Figure 2-TI shows the area that includes the group of accumulative curves of these sediments. The mean grain-size of the samples varies between 4.91 ϕ and 6.12 ϕ (average 5.30 ϕ). According to the grading of FOLK and WARD (1957), the sorting of these sediments is poor (1.58 ϕ).

Mineralogically, the analyzed samples have certain differences according to their position. In the central area of the section (km 3.6–6.4), where the erosional surface is deeper (Figure 2), it was found that the most abundant grains correspond to alterites and quartz. Feldspar, heavy minerals and volcanic glass were determined in subordinate proportions, not exceeding 17% in any case (Figure 2, MII). However, in the samples obtained between km 0 and 3.5 and between km 6.4 and 9 sectors where the compact sediments are at shallower depth (approximately between 9 and 18 m), a clear predominance of volcanic glass (34%) is noted (Figure 2, MI). The grains of alterites and quartz are secondary in abundance. On the other hand, the high quantity of $CaCO_3$ (approximately 23%) in this sandy silt which can be defined as calcrete is another mineralogical difference with the substratum material found between km 3.6 and 6.4 of the studied section.

On the pre-Holocene facies between km 3.5 and 7.5 (Figure 2), there is a sediment of 10YR 5/4 Moderate Yellowish Brown coloration, composed of fine to very fine sand with a low percentage of silt-clay (< 10%). This deposit of lenticular form in the studied section has its greatest thickness (7 m) in km 4.9. This material is found loose and in some sectors weakly compacted. Also, it is usual to find some small pebbles of siltstone and very fine sandstone in the lower levels. Their size does not exceed in any case 1 cm of diameter and they have subangular to subrounded shapes.

Grain-size analysis performed to suitable samples showed a granulometric similitude of the whole deposit. The cumulative distributions are located in a very narrow band (Figure 2-TII). The values of the mean vary between 1.44 ϕ and 3.55 ϕ (average 2.30 ϕ). The smallest results of the mean correspond to those samples that contain some proportion of gravel. The sorting of the material is poor (1.24 ϕ). The mineralogy of the sandy material is similar to the underlying compact substratum (Figure 2-TII and 2-MIII).

The paleontologic content of the sediments is limited, as only vestiges of mollusc shells were observed. Due to their small size and degree of abrasion, it is not possible to identify species. The remains of ostracod are also limited; only the identification of *Limnocythere* sp. was possible. The diatomological analysis established that this material is "poor" in diatoms. Fifty-six percent corresponds to fresh or brackish water species. Epiphytic and benthonic diatoms were found, among them: *Amphora ovalis, Cyclotella ocellata, Hantzschia amphioxys, Cocconeis placentula, Epithemia sorex, Navicula cuspidata, Pinnularia* sp., *Rhopalodia gibba, Surirella* sp. The rest (44%) are euhalobias marine species (salinity 30‰–40‰), littorals and planktonics. They are: *Actinoptychus* sp., *Cocconeis disculus, Cocconeis speciosa, Coscinodiscus* sp., *Diploneis smithii, Navicula cincta, Nitzschia punctata, Opephora* sp., *Paralia sulcata, Podosira stelliger, Raphoneis amphiceros, Rhaphoneis surirella, Thalassiosira* sp.

Overlying this sediment and the pre-Holocene basement, estuarine marine facies are found at the northwest and southeast sections of the studied profile. In the northwest sector (between km 0–1) there are small lens (Figure 2), composed of gravel (61%), sand (28%) and silt-clay (11%). Generally, the pebbles consist of silt, their shapes are subrounded to subangular, and their size does not exceed 1.5 cm. In some cases, they have a high percentage of calcium carbonate. Small shell remains are abundant. The characteristic cumulative distributions of this material are observed in Figure 2-TIII (mean: 0.62 ϕ, standard deviation: 2.47 ϕ). Towards the southeast, a medium sand with gravel, colour 10YR 2/2 Dusky Yellowish Brown was found near km 1 (Figure 2). The pebbles are of the same type as those found at northwest. The average of the mean of the samples is 1.33 ϕ, while its sorting is poor (1.80 ϕ) (Figure 2, TIII).

In the sector in which the surface of the substratum has a slope of 0.5° towards the northwest (between km 3.1 and 3.3), the sediment, colour 10YR 2/2 Dusky Yellowish Brown changes laterally to fine-very fine sand (Figure 2). The mean grain size of the samples varies between 2.30 ϕ and 3.56 ϕ (average 2.74 ϕ). In general its sorting is moderately good (0.80 ϕ) (Figure 2, TIV).

From km 5.5 of the studied section, the fine material abundance increases transitionally. Also, the quantity of pebbles increases (25%), especially near the pre-Holocene compacted sediment. The pebbles do not exceed 1.5 cm of diameter, are subrounded to subangular, and their composition is similar to the underlying sediment. On the other hand, it must be mentioned that a high percentage of these clasts is found partially covered by bryozoa or by small calcareous tubes (serpulids remains). From a granulometric standpoint, this deposit is very homogeneous, some samples having greater concentrations of coarse sand and gravel (Figure 2, TV). The mean varies between 3.33 ϕ and 4.51 ϕ (average 3.87 ϕ), while its sorting is very poor (3.69 ϕ).

The estuarine marine sediments contain a high percentage of mollusc shells and fragments. Other organisms are found in minor proportion: cnidaria, bryozoa, annelida, cirripedia and ophiuroidea. Their environment corresponds to the littoral-marine. All the species determined are similar to those found in the Holocene sand shell ridges of the estuary coast between 8 and 9 m above the sea level (ALIOTTA and FARINATI, 1990).

The material shows significant granulometrical differences, but from the mineralogical standpoint, they are similar. Alterites and quartz are dominant (Figure 2, MIV), followed in importance by volcanic glass, feldspar and heavy minerals (hypersthene, augite and opaques).

In the upper part of the stratigraphic section (Figure 2), the sediment has a high percentage of fine fraction (colour 10YR 4/2 Dark Yellowish Brown). In general, this corresponds to a clayey-silty sand. The lowest level has a somewhat undulatory laminated structure. The lamination is thin (less than 0.2 cm) and is composed of silt-clay (brown) and fine sand (greyish brown). In some parts, the clay fraction is dominant, contributing to the high plasticity of the material. The thickness of this layer is variable and has its greatest thickness to the southeast of the section (approximately 9 m) (Figure 2). The value of the mean varies between 6.20 ϕ and 7.88 ϕ, average 6.91 ϕ. The slope of the accumulative frequency curve (Figure 2, TVI) indicates a very poor sorting (2.26 ϕ). Mineralogically, the sand fraction is dominated by volcanic glass and quartz (Figure 2, MV). The clay fraction comprises mainly montmorillonite and illite, with a small proportion of kaolinite.

DISCUSSION AND CONCLUSIONS

Very compact sandy silt, in some places strongly cemented with calcium carbonate, forms the pre-Holocene basement of the unconsolidated sedimentary sequence in the inner area of the Bahía Blanca Estuary. Coastal hydrogeological drillings carried out by the "Dirección Nacional de Geología y Minería", together with seismic data of the Principal Channel (NEDECO-ARCONSULT, 1983), revealed the continuation of this basement towards the continental shelf along the coastal area of the estuary. Thus at its mouth, ALIOTTA and PERILLO (1992) found this sedimentary rock exposed in the sea bottom at between 13 and 18 m of depth.

The basal siltstone does not present significant textural and macroscopic variations in the study area, only differences based on the mineralogical characteristics (calcium carbonate as cementing element and percentage of volcanic glass). The materials located above 18 m of MSL are assigned to the Pleistocene (Pampiana Formation), while the deeper sector of the basement corresponds to Tertiary sediments (late Miocene-Pliocene, Chasicó Formation) (ALIOTTA *et al.*, 1992). Both formations correspond to an eolian-fluvial sedimentary paleoenvironment (ZAMBRANO, 1972; FIDALGO *et al.*, 1985) and between them there is not a distinguishable lithoestratigraphic discontinuity. The rocky substratum found in the estuary is an ancient abrasion shelf on which unconsolidated sediments were unconformably deposited. This erosive surface extends regionally to the inner estuary (Figure 3) and has a mild slope towards the south of approximately 0.1°–0.2° (ALIOTTA *et al.*, 1987; ALIOTTA and FARINATI, 1990; FARINATI *et al.*, 1992; CHAAR *et al.*, 1992).

Sedimentary facies with very changeable textural characteristics are distributed over the Plio-Pleistocene erosional surface along the study section. The analysis and relationships of these stratigraphic units reflect the nature of the sedimentary environmental and Quaternary coastal changes.

Where the rocky basement is found at greater depth (between km 3.5 and 7.5, Figure 2), the older unconsolidated sediment is found, forming a lenticular deposit in the study section. This is composed by a fine-very fine sand with less than 10% of mud. The remnants of mollusc shells are very scarce and unidentifiable. On the other hand, it was only possible to determine the presence of one fresh water ostracod (*Limnocythere* sp.). Therefore, the diatom analysis carried out indicated a high concentration of diatom taxa of clearly nonmarine affinity, not very easily found in the present chemical conditions of the estuary. This allowed us to define a dominant fluvial sedimentary paleoenvironment in which the marine conditions are subordinated. At the beginning of the deposition of this material, the environmental energy was high enough to erode the underlying basement, incorporating pebbles and lithic fragments of the compacted substratum into the sediments. The high competency of the transport agent of this paleoenvironment is reflected in the values of percentile 1 (Figure 2, TII). According to the sequence indicated by ALLEN *et al.* (1973) in the Gironde Estuary, this high-energy fluvially dominated facies can be associated with an upper estuary or estuarine fluvial sector, with alluvial current dominance attenuated by tidal flow.

Satellite images east of the studied area show an elongated east-west depression, longer than 120 km, and morphologically related to the inner part of the present estuary. This depression would form part of the ancient Colorado River Delta (its present mouth is located 100 km south of Bahía Blanca, Figure 1). In this paleoenvironment, the interaction of fluvial, marine and aeolian processes is invoked to explain a complex geological history of the area that makes its characterization difficult (GONZÁLEZ URIARTE, 1984). Fluvial-estuarine facies, defined between km 3.5 and 7.5 of the study section, probably correspond to a paleoenvironment formed before the last great post-glacial transgression in a period where the sea level was lower than the present one.

In general, the modern estuaries of the world were formed during the most recent rise of sea level which began about 15,000 a ago, a period of deglaciation, from a depth of 100–130 m to its present position (NICHOLS and BIGGS, 1985). In particular, radiocarbon data on the Argentine continental shelf (URIEN and EWING, 1974) and paleontological core registers (BOLTOSKOY, 1973) established that at 11,700 ± 500 a B.P. the rise of sea level began, from approximately 140 m below the present level. The dominantly fluvial sedimentary paleoenvironment located as deep as 24 m below present sea level (Figure 2) indicates that this deposit would have been formed when the sea was at approximately 30 m below the present level. Considering this depth and in agreement to the pattern of world-wide sea level during the Holocene epoch (BELKNAP and KRAFT, 1977), the probable age of fluvial estuarine sediments is Early Holocene.

Marine waters gradually invaded the fluvial paleoenvironment during the rise of the Holocene sea, resulting in the deposition of estuarine-marine sedimentary facies. Therefore, in the sector of the profile studied where the Pleistocene is shallower (km 0.2–3, Figure 2), a medium sand, poorly sorted and with abundant remnants of small shells is found. At the basal level of the stratum, there are siltstone pebbles coming from the Pleistocene abrasion platform formed during the be-

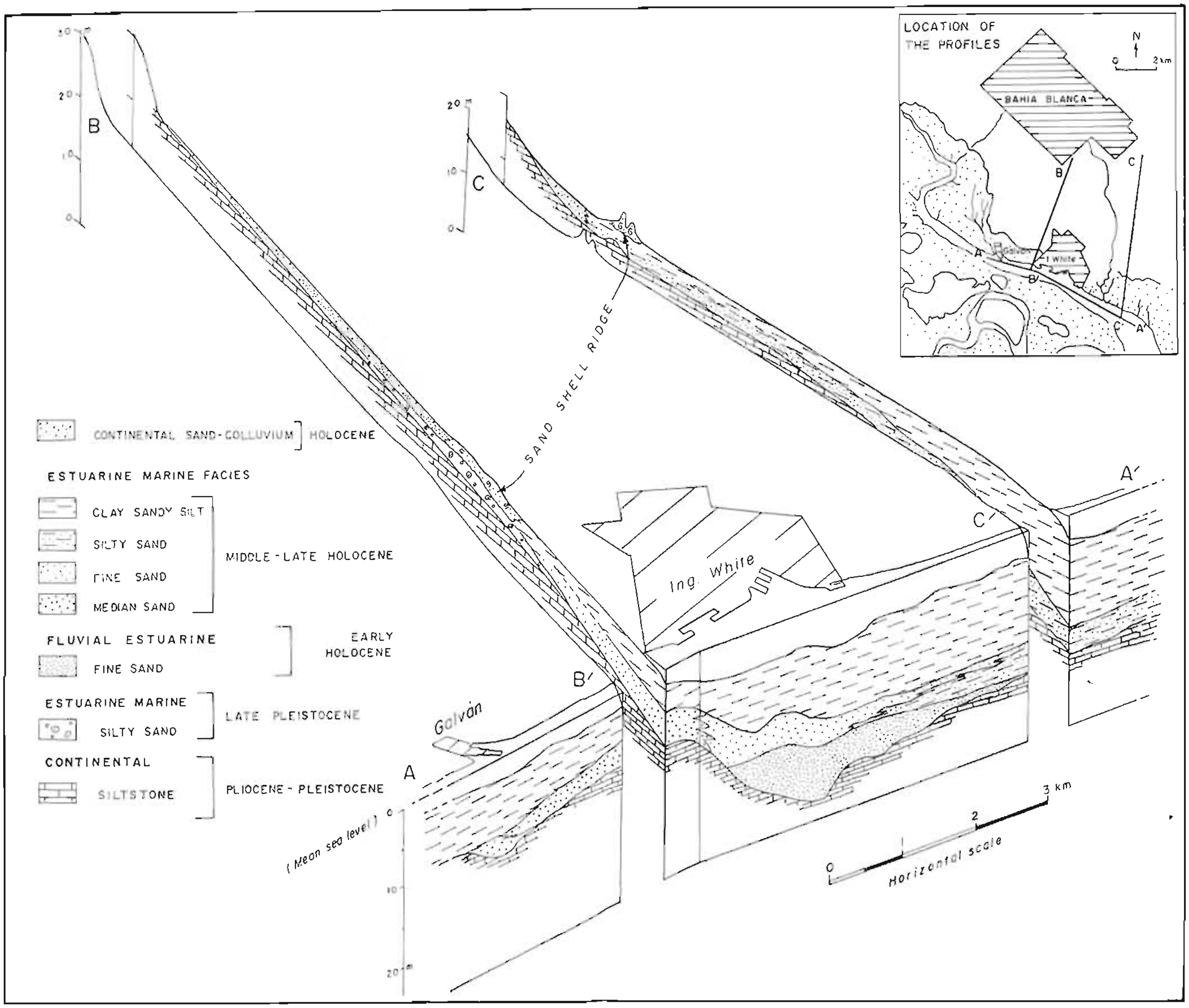

Figure 3. Schematic diagram showing the stratigraphical model of the Bahía Blanca Estuary.

ginning of the transgression. These pebbles, crushed shells and the absence of mud in this sediment indicate paleoenvironmental conditions with moderate-high wave energy. In particular, an elevated concentration of pebbles and shells appears to the northwest, inside a concavity carved in the basal Pleistocene sediments. We related these materials to an inlet of an ancient coastal creek or to a Holocene tidal channel, with a high erosive power.

Towards the mouth of the estuary, from approximately Ing. White Harbor, the Holocene transgressive facies change laterally to a well-sorted fine-very fine sand, increasing the proportion of mud to the SE of the study section (Figure 2), which reflects hydrodynamic paleoenvironmental conditions of low-energy. However, this material overlies the Plio-Pleistocene hard substratum in a random pattern and contains siltstone pebbles covered with bryozoa or small calcareous tubes. During the initial stage of the transgression, the marine erosive process incorporated the pebbles and lithic fragments from the bedrock. Later these conditions were reduced to such a level that the organisms could form their colonies in an environment of low energy and sedimentation rate.

After the deposition of the sand and gravel facies, the sedimentation of the mud facies reflects the decreasing energy of deposition, increasing the sediment transport in suspension, and being less dependent on the bedload. This was probably the result of increasing water depth as function of rising sea level. The sedimentary structures, *i.e.*, flaser and sand-mud lamination (particularly present in the higher levels of the mud facies), suggest the effect of tidal currents. In this tidal bedding, the sand layer is deposited by asymmetrical bidirectional tidal currents (flood or ebb) for half of a tidal cycle and the mud layers represent deposition from suspension at times of tidal slack (SHI, 1991).

In the coastal area of the estuary, the sandy facies found in the Principal Channel are laterally correlated towards the north with a silty fine sand (ALIOTTA *et al.*, 1987; FARINATI *et al.*, 1992), which lies unconformably on the Pleistocene basement (Figure 3, C-C′ profile). This sediment, belonging to the initial period of the last transgression when the sea overcame the present level (it was found up to 5 m above MSL), reflects littoral conditions of low wave energy, while tidal currents are the main means of transport and deposition of the sediments (ALIOTTA and FARINATI, 1990).

As observed by CLIFTON (1983) and DEMAREST *et al.* (1981), estuarine deposits rarely consist of a single fill complex formed at only one high sea stand; and, at least during the Pleistocene and Holocene, it seems that the estuarine environments reoccupied the same places as they had during various other transgressions. So, in the coastal area of the estuary of Bahía Blanca, above MSL (up to 14.5 m), estuarine-marine deposits corresponding to the late Pleistocene (^{14}C ages between 35,000 a B.P. and 25,700 a B.P., GONZÁLEZ, 1984; CHAAR *et al.*, 1992) stand discordantly on continental sediments (Pampiana Formation) (Figure 3, B-B′ profile). These sediments of the marine Pleistocene do not have a well-defined lateral continuity and are present in a broken pattern in the area south of Bahía Blanca (GONZÁLEZ, 1984). Thus, in the coastal sector to the east of Ing. White, these materials are not present (Figure 3, C-C′ profile). It is important to note that the marine sediments belonging to the Pleistocene are not found in the sedimentary sequence of the Principal Channel of the estuary. We think that the material of the marine Pleistocene existent in the coastal zone, above sea level, would correspond to deposits located in the sectors more protected from the active erosional processes which occurred during the last post glacial transgression.

The maximum Holocene transgression is represented by sand-shell ridges deposited on the coastal area (Figure 1), to an altitude of approximately 10 m above MSL. This episode has a geological age of 5,990 a B.P. (GONZÁLEZ, 1989). Such geoforms were unconformably deposited on cemented Pleistocene marine sediments or on clayey-sandy silt of the Holocene tidal flat (Figure 3).

The progradation of the Holocene tidal flat (^{14}C datings on valves of mollusc in life position indicate ages of 3,850 to 3,373 a B.P., GONZÁLEZ *et al.*, 1983; FARINATI, 1985) and the progressive decrease of sea level uncovered a great coastal flat, which is the characteristic geoform of the inner area of the estuary. Also, tidal channels of several dimensions were formed where the flood and ebb currents regulate the present sedimentary dynamics. The fine sediments of this present tidal flat grade to those of ancient deposit during the post glacial transgression-regression. The latter can be observed exposed in different channels of the estuary due to intensive erosional processes (GINSBERG and PERILLO, 1990). In those places where sedimentation prevails, only the degree of compaction of the deposits differentiates the age of both sediments.

In accordance with the source of sediment to an estuary (RUSNAK, 1967), the sedimentary sequence studied in Bahía Blanca can be related with an "inverse filled basin", in which Holocene sediments accumulate principally from the longitudinal distribution of sediments entering from the sea. On the other hand, the stratigraphic sequence of the Bahía Blanca Estuary is in accordance with the vertical sequence of sedimentary lithofacie established by NICHOLS and BIGGS (1985) in a transgressive estuarine environment.

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