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# HOLOCENE EVOLUTION OF THE CAORLE BARRIER-LAGOON (NORTHERN ADRIATIC SEA, ITALY)

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*Key-words*: Litho-biofacies, $^{14}C$ age, Environmental zonation, Holocene, Lagoon, Adriatic Sea.

*Riassunto*. Dati litostratigrafici, paleoecologici e cronostratigrafici ottenuti dallo studio del sondaggio A (10 m di profonditá) permettono di ricostruire con dettaglio le vicende evolutive dell'immediato sottosuolo del cordone litorale della laguna di Caorle. Dal riconoscimento dell'evoluzione delle organizzazioni zonali evidenziate dalle forme lagunari (molluschi, ostracodi, foraminiferi) rinvenute nel sondaggio, emerge che la laguna di Caorle si è formata almeno nel Boreale e si è evoluta fino ai giorni nostri con una leggera retrogradazione del margine lagunare, fino a quando è stata bonificata.

*Abstract*. The study of borehole A (10 m deep) evidences lithological, paleoecological and chronostratigraphical data useful to interpret the evolution of lagoon deposits in the subsoil of the barrier island of the Caorle Lagoon. By the identification of the zonal organizations of the faunae (molluscs, ostracods and foraminifers) in the borehole, it appears that Caorle Lagoon originated at least during Boreal evolving in a feeble retrogradation of the lagoon borders, up to the moment it was reclaimed, few years ago.

## Introduction.

The littoral area of Valle Vecchia is located in the north-eastern area of the Venetian plain. It was once the old barrier island of the recently reclaimed Caorle Lagoon. This microtidal lagoon (tidal range ca 1 m) is located in a N-S restricted band subparallel to Nicessolo Channel and, today, evidences a strong reclamation (fisheries Valle Nuova, Valle Grande, Zignago and Valle Perera). In agreement with the Kyerfve's classification (1986), the coastal Caorle Lagoon can be defined an artificial chocked system fed by one inlet only.

Upon the barrier island the soils are mostly constituted by ancient bottoms of lagoon, which presently reach 2 m below M.S.L. Moreover, the sinking entity is unknown since this area was strongly reclaimed. However, the reclamation of the nearby areas of the Friuli region caused a compaction of the deposits and a soil sinking of 0.3-1.5 m in the last 60 years (Foramitti, 1990). A multidisciplinary approach (supported by the C.N.R. program "Sistema Lagunare Veneziano") plans to interpret the recent evolution of the Caorle area and to compare it with the recent geological history of other littoral areas of the easternmost part of north Adriatic Sea (Marocco, 1991) and of Venetian coast (Alberotanza et al., 1977; Tosi, 1994).

Within this program, four continous-coring boreholes have been drilled along a N-S transect, from Portogruaro to Valle Vecchia (Fig. 1) down to a depth of about 10 m from the soil surface. This paper focuses on the stratigraphy of the borehole A, which is located seaward behind the barrier island of Valle Vecchia (45°37'37" N, 12°57'00" E), and represents the first step of the research. Its aim is: i) to identify the principal lithofacies and biofacies (molluscs, ostracods and foraminifers) of the deposits; ii) to highlight the effective meaning of the different data obtained; iii) to combine all the data, together with the radiocarbon data ($^{14}C$) in order to reconstruct the chronostratigraphic and paleoenvironmental evolution of the sedimentary sequence.

## Material and methods.

Ten cores of the borehole A have been cut and described (Fig. 2 and Fig. 3).

Sediment slices of 2-3 cm have been sampled for grain-size, mineralogical, paleontological (molluscs), micropaleontological (ostracods and foraminifers), and radiocarbon datation analyses (Fig. 4).

Samples for the grain-size analysis were collected in correspondence of lithological changes. The data are obtained through the standard method sieve-sedigraph and elaborated in agreement with Nota (1958) classification. After the preliminary results, the lithostratigraphical codes have been selected within the Miall (1992) and

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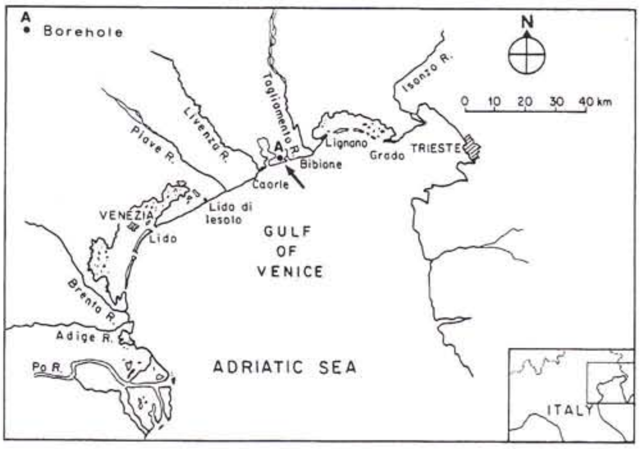

Fig. 1 - Sketch map of the northern Adriatic Sea. The circle marks the location of the Valle Vecchia littoral borehole A.

Johnson (1978) scheme of stratigraphic notation concerning fluvial-lacustrine and sublittoral deposits, respectively.

The fraction 50-210 μm of the sandy samples were also subjected to mineralogical analysis by flotation in tetrabromethane (specific gravity = 2.95) and successive calculation on 100 grains at least in order to define the heavy minerals in agreement with Gazzi (1966).

The paleontological analysis concern samples collected in correspondence of lithological changes and in other selected organogenous levels. The samples were washed through sieves of 500 and 62 μm. The corresponding washing residues were studied to define molluscs and microfaunae (ostracods and foraminifers) respectively. The foraminifers were studied quantitatively on a sub-sampling of 300 specimens; the ostracods are studied semiquantitatively in all the samples; the molluscs were reported in terms of presence only.

Radiocarbon dates have been accomplished in the Laboratoire d'Hydrologie et de Géochimie Isotopique (Université de Paris Sud) on mollusc specimens (*Cerastoderma glaucum*) and peat (debris of *Cymodocea nodosa*) at the core-depth of -1.16, -3.19, -6.04 and -7.78 m below M.S.L. The conventional ages are calibrated in the time-span 0-9000 yrs using the program CALIB 3.0.3 (Stuiver & Reimer, 1993).

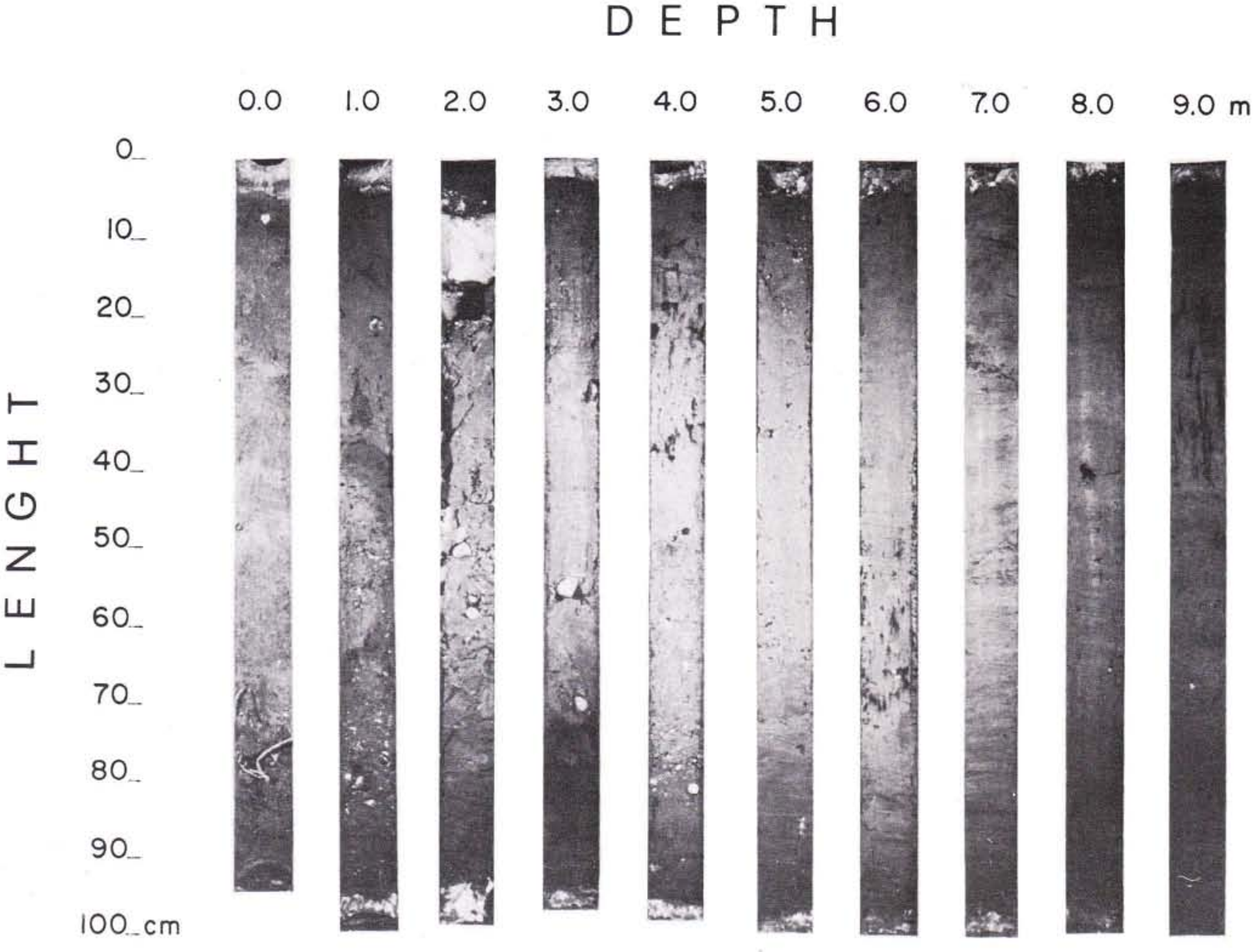

Fig. 2 - Photo of the cores of borehole A. The depth and lenght are reported.

**Lithostratigraphy.**

The data obtained from the study of the sections of the borehole A reveal that such borehole consists of two sedimentological intervals (A1 and A2) separated by a pedogenetic horizon at -0.14 m from M.S.L.

The lower interval A1 (-9.40/-0.14 m from M.S.L.) is characterized by a continuous sequence of very dark gray (see Munsell Soil Chart, color 2/5 Y 3/0) pelites, i.e. lithofacies C, interbedded to bioturbated gray (2/5 Y 5/0) sandy pelites (lithofacies Mb), which become thickly laminated (lithofacies Ma) at a core-depth of -7.34/-6.50 m. These deposits are also characterized by a constant occurrence of geminate gypsum crystals. This sequence presents very abundant plane-parallel and rarely inclined stratificated fragments of phanerogams, polychaete tubes, and numerous molluscs, which become very abundant at a core-depth of -5.30/-0.86 m. At the top, this interval presents a dark grayish brown (2.5 Y 4/2) soil (lithofacies P; Fig. 3) with vertical roots, rounded pebbles and abundant mottles. It can be considered a pseudogley soil. Interval A1 may indicate a mud flat of microtidal lagoon.

The upper interval A2 (-0.14 to +0.64 m from M.S.L.) is characterized by massive and subordinate slightly plane-parallel stratificated medium-fine grayish brown (2.5 Y 5/2) sands. Topward, abundant and bad-preserved molluscs are present; at the bottom, pelite lumps, carbonous concretions and vertical roots are found. Thus, this interval shows a negative gradation and a Sb lithofacies (Johnson, 1978; Fig. 3).

The mineralogical analysis points out an assemblage garnet-augite, with ultrastable minerals (zircon, and rutile) and low values of picotite. This mineral assemblage shows a composition similar to the one which forms the deposits of the Tagliamento R. mouth (Gazzi et al., 1973). This interval indicates a sedimentary environment such as back dune and its sands might be beach deposits coming from Tagliamento R.

**Biostratigraphy.**

Molluscs.

In relation to the reduced amount of sediment studied for each core-level the molluscs are reported in terms of presence only (Tab. 1). The levels sampled are the same studied from the micropaleontological point of view, together with other selected for their evident abundance of molluscs (see P samples of Fig. 3). Save for few levels, the molluscs are present in all the borehole and are mostly represented by species which are

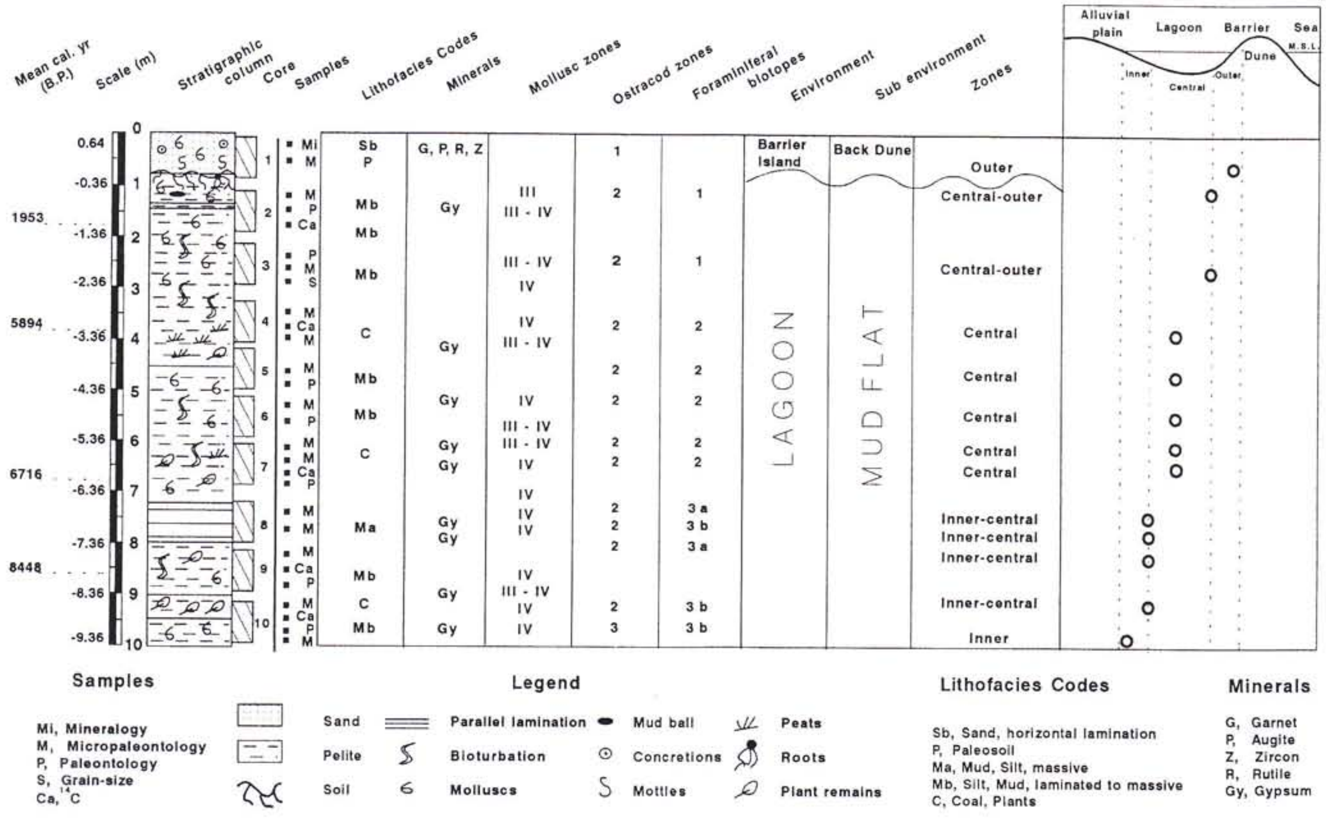

Fig. 3 - Log of borehole A, showing the sedimentological, mineralogical, paleontological, micropaleontological, paleoenvironmental and chronological results.

| interval depth<br>(m from M.S.L.)<br>taxa | -9.28<br>-9.26 | -9.06<br>-9.01 | -8.48<br>-8.46 | -8.05<br>-7.94 | -7.63<br>-7.61 | -7.28<br>-7.26 | -6.88<br>-6.86 | -6.26<br>-6.16 | -5.78<br>-5.76 | -5.58<br>-5.56 | -4.98<br>-4.86 | -4.68<br>-4.66 | -4.16<br>-4.06 | -3.98<br>-3.96 | -3.28<br>-3.26 | -2.86<br>-2.84 | -2.20<br>-2.18 | -1.95<br>-1.84 | -1.06<br>-1.01 | -0.98<br>-0.96 | 0.23<br>0.25 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Gibbula adriatica* (Philippi, 1844) | | | | | | | | | | | | | | | | | | * | * | | |
| *Gibbula* sp. | | | | | | | | | | | | | | | | | | | | * | |
| *Tricolia tenuis* (Michaud, 1829) | | | | | | | | | | | | | | | | | | * | | | |
| *Alvania semistriata* (Montagu, 1808) | | | | | | | | | | | | | | | | | | * | | | |
| *Pusillina marginata* (Michaud, 1832) | | | | | | | | | | | | | | | | | | | | * | |
| *Hydrobia acuta* (Draparnaud, 1805) | | | * | | | | * | | | | | * | | | | | | | | | |
| *Ventrosia ventrosa* (Montagu, 1803) | | * | | * | * | * | | * | * | * | * | * | * | * | | * | | * | * | | |
| *Heleobia stagnorum* (Gmelin, 1791) | | | | | | | | | | | * | | | | | | | | | | |
| *Truncatella subcylindrica* (Linné, 1767) | | | | | | | | | * | | | | | | | | | | | | |
| *Bittium reticulatum* (Da Costa, 1778) | | | | | | | | * | | | | | | | | | * | * | * | * | |
| *Bittium scabrum* (Olivi, 1792) | | | | | | | | | | * | | * | | | | | * | | | * | |
| *Cerithium vulgatum* Bruguière, 1792 | | | | * | | | | | | | | | * | | | | | * | | | |
| *Retusa mammillata* (Philippi, 1836) | | | | | | | | | | | | | | | | | | * | | | |
| *Retusa semisulcata* (Philippi, 1836) | | | | * | | | | * | | | * | | * | | | | | * | * | | |
| *Retusa* sp. | | | | | | | | | * | * | | | | * | | * | | | | | |
| *Chrysallida* sp. | | | | | | | | | | | | | | | | | | * | * | | |
| *Pulmonata* | | | | | | | | * | | | | | | | | | | | | | |
| *Chlamys* sp. | | | | | * | | | | * | | | | | | | | | | | | |
| *Lucinoma boreale* (Linné, 1767) | | | | | | | | | | | | | | | | | | | | * | |
| *Loripes lacteus* (Linné, 1758) | | | | * | | | | | | * | * | | * | | | | | * | * | | |
| *Mysella bidentata* (Montagu, 1803) | | | | | | | | | | | | | | | | | * | | | | |
| *Pavicardium exiguum* (Gmelin, 1791) | | | | | | | | | | | | | | | | | * | | | | |
| *Plagiocardium papillosum* (Poli, 1795) | | | | | * | | | * | | | | | | | | | | | | | |
| *Cerastoderma glaucum* (Poiret, 1789) | | | | | * | | | | | | | | * | | | | | * | * | | |
| *Scobicularia plana* (Da Costa, 1778) | | | | | | | | | | | | | | | | * | | | | * | |
| *Abra segmentum* (Récluz, 1843) | | * | | * | * | * | | * | * | | * | * | * | * | | * | * | * | * | | |
| *Gouldia minima* (Montagu, 1803) | | | | | | | | | | | | | | | | | | | * | | |
| *Dentalium* sp. | | | | | | | | | | | | | | | | | | | * | | |

Tab. 1 - Distribution of molluscs listed in systematic order proposed by Sabelli et al. (1990).

very common in brackish-water settings (*Abra segmentum, Cerastoderma glaucum, Heleobia stagnorum, Hydrobia acuta, Loripes lacteus, Parvicardium exiguum, Scrobicularia plana* and *Ventrosia ventrosa*). Following Pérès & Picard (1964), the stocks *Abra segmentum/Cerastoderma glaucum/Scrobicularia plana* and *Loripes lacteus/Parvicardium exiguum* can be included in LEE (Lagunaire Eurytherme Euryhalyne) and SFMC (Sable Fins de Mode Calme) paleobiocoenoses, respectively. Thus, the constant occurrence of such species indicates a continuous sequence of settings of lagoon along the borehole, often characterized by vegetated floors as demonstrated by the constant presence of other species (*Alvania semistriata, Bittium reticulatum, Bittium scabrum, Gibbula adriatica, Pusillina marginata*) (Pérès & Picard, 1964).

Guelorget & Perthuisot (1983) proposed a zonal distribution of the paralic taxa in the lagoon environments based on the concept of confinement. Within the paralic taxa, some mollusc species found in the borehole A are considered as markers of well defined zones: *Loripes lacteus* and *Scrobicularia plana* are present in the Zone III established by the latter authors, meanwhile *Abra segmentum, Cerastoderma glaucum* and *Hydrobia acuta* in their Zone IV. Analyzing the occurrence of such species in the borehole, two zones (III and IV) and a transitional area (III/IV) between them have been identified.

Zone III testifies an area of lagoon characterized by marine influence, meanwhile zone IV indicates an inner area which represents a lagoon environment *sensu stricto* near the fluvial incomes. The transitional area III/IV represents intermediate environmental conditions between III and IV.

Both marine and fluvial influence are also confirmed by the presence of displaced marine (*Gouldia minima, Lucinoma boreale, Mysella bidentata*) and pulmonate forms, respectively in the upper and the lower part of the borehole A.

Thus, this borehole displays a sequence of mollusc zones which indicate a typical lagoon area with fresh-waters inputs (zone IV) with frequent episodes of slightly increased marine influence (zone III/IV) in almost all the interval A1, excepted for the upper part of the core 2 where the lagoon evolves towards an area (zone III) characterized by an evident marine influence.

### Ostracods.

The ostracods have undergone qualitative and semiquantitative analysis (Tab. 2), giving as result the detection of three ostracod assemblages. The species which constitute these assemblages are considered autochthonous for the contemporary presence of adult and juvenile instars in the sample. On the contrary, other species represented by isolated adult valves, without their juveniles, juvenile or bad-preserved forms are considered displaced. The assemblages are described below.

| interval depth | -9.28 | -8.48 | -7.63 | -7.28 | -6.88 | -5.78 | -5.58 | -4.68 | -3.98 | -3.28 | -2.86 | -2.20 | -0.98 | 0.23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (m from M.S.L.) | -9.26 | -8.46 | -7.61 | -7.26 | -6.86 | -5.76 | -5.56 | -4.66 | -3.96 | -3.26 | -2.84 | -2.18 | -0.96 | 0.26 |
| species | | | | | | | | | | | | | | |
| *Callistocythere adriatica* Masoli, 1968 | | | | | | | | | | | | | | * |
| *Cistacythereis (H.) turbida* (G.W. Müller, 1984) | | | * | | | | | | | | | * | | |
| *Cyprideis torosa* (Jones, 1850) | vn | n | vn | n | vn | vn | vn | vn | vn | | vn | n | vr | * |
| *Cytherois frequens* G.W. Müller, 1894 | | | vr | * | | | | | | | | | | |
| *Cytheromorpha* sp. | | | | | * | | | | | | | | | |
| *Leptocythere bacescoi* (Rome, 1942) | | | | vr | vr | vr | vn | vn | n | | | n | | |
| *Leptocythere bituberculata* B., C. & M., 1976 | | | vr | | r | | | * | | | | | | * |
| *Leptocythere lagunae* Hartmann, 1958 | | | | * | | | n | | vr | | | vr | | |
| *Leptocythere ramosa* (Rome, 1942) | | | | n | n | * | vr | n | r | | | vr | | |
| Leptocytherid sp. 1 | | | n | | vn | | vr | | | | | vr | | |
| *Loxoconcha elliptica* Brady, 1868 | vr | | n | | n | n | n | vn | n | | | vr | | |
| *Loxoconcha rhomboidea* (Fischer, 1855) | | | | | | | | | | | | * | | |
| *Loxoconcha stellifera* G.W. Müller, 1894 | | | | | | | | | * | | * | vr | | |
| *Pontocythere turbida* (G.W. Müller, 1894) | | | | | | | | | | | | * | | vr |
| *Propontocypris* sp. | | | | | | | | | | | | * | | |
| *Xestoleberis communis* G.W. Müller, 1894 | | | | | | | | | | | | | * | |
| *Xestoleberis dispar* G.W. Müller, 1894 | | | | * | * | * | * | * | vr | | | vr | | |

Tab. 2 - Distribution of the ostracods in borehole A (in alphabetical order). The autochthonous species are reported as "vr" (very rare), "r" (rare), "n" (numerous) and "vn" (very numerous). The displaced species are indicated with an asterisk (*).

**Assemblage "a".** This assemblage consists of *Cyprideis torosa* (Pl. 1, fig. 1), *Leptocythere bacescoi* (Pl. 1, fig. 2), *Leptocythere ramosa*, *Loxoconcha elliptica* (Pl. 1, fig. 4) and Leptocytherid sp. 1 (Pl. 1, fig. 6), which show the widest diffusion; some other species that show rather occasional occurrence within this assemblage are *Cytherois frequens*, *Leptocythere bituberculata* (Pl. 1, fig. 3), *Leptocythere lagunae* and *Loxoconcha stellifera*. The combination of typical brackish-water species (*Cyprideis torosa*, *Loxoconcha elliptica*, *Leptocythere lagunae* and *Loxoconcha stellifera*), together with some other species characteristic of marine coastal settings (*Leptocythere bacescoi* and *Leptocythere ramosa*) indicates brackish-water environment with relevant marine influence. The presence of scattered displaced marine forms, including *Cistacythereis (Hiltermannicythere) turbida*, *Pontocythere turbida* (Pl. 1, fig. 5) and *Propontocypris* sp., validates this interpretation.

**Assemblage "b".** The second assemblage consists of *Cyprideis torosa* with or without *Loxoconcha elliptica*. This ostracod fauna is characteristic of brackish-water environment with considerable fresh-waters inputs.

**Assemblage "c".** This is a monospecific assemblage with very rare specimens of *Pontocythere turbida*, a marine shallow-water species which dwells elevated bottom energy marine environments. Displaced brackish-water forms (*Cyprideis torosa*) are simultaneously recorded. The coincidence of sporadic autochthonous *Pontocythere turbida* and displaced *Cyprideis torosa* within the same area testifies a high energy brackish-water setting with very elevated sea waters inputs.

The assemblages recorded are them all characteristic of brackish-water settings (see above). Their composition allow to assume more properly a lagoon environment, as demonstrated by Montenegro & Pugliese (in press) in the Marano and Grado lagoons. Moreover, these assemblages might be correlated to the zonal distribution indicated by Montenegro (1995) and Montenegro & Pugliese (in press) in the previously cited lagoons, where every single assemblage is closely related to a very well defined environmental zone. They established three zones, from the sea into landward. Following their method, the ostracod assemblages which usually dwell zones strongly influenced by the marine water incomes, located near the sea, are associated to zone 1; zone 2 corresponds to some areas of the lagoon affected by both, marine and fresh-waters inputs, and is clearly colonized by assemblages of species which tolerate alternated marine and fresh-water influences depending on the tides; assemblages which live in settings characterized by elevated fresh water inputs define lagoon environments usually located near the internal borders which comprehend zone 3.

Applying this latter zonal distribution to the analysis of the ostracod fauna recorded in the borehole A, the existence of three zones, all of them within the lagoon environment, have been evidenced: the assemblage "a" is characteristic of zone 2; assemblage "b" corresponds to zone 3; assemblage "c " is related to zone 1.

It is thus possible, as reported in Fig. 3, to hypothesize on the borehole A the following paleoenvironmental sequence, proceeding from the bottom to the top:

- core 10 shows the presence of assemblage "b", characteristic of zone 3, which determines lagoon environments located near the internal borders.
- the subsequent cores (9 to 2) present the assemblage "a", which is related to zone 2; this zone corresponds to some areas of the lagoon affected by both ma-

| interval depth (m from M.S.L.)<br>species | -9.28<br>-9.26 | -8.48<br>-8.46 | -7.63<br>-7.61 | -7.28<br>-7.26 | -6.88<br>-6.86 | -5.78<br>-5.76 | -5.58<br>-5.56 | -4.68<br>-4.66 | -3.98<br>-3.96 | -3.28<br>-3.26 | -2.86<br>-2.84 | -2.20<br>-2.18 | -0.98<br>-0.96 | 0.23<br>0.26 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Adelosina dubia* (d'Orbigny, 1826) | | | | | | | | | | | | 3.8 | | x |
| *Ammonia beccarii tepida* (Cushman, 1926) | 100.0 | 95.4 | 69.3 | 94.3 | 61.0 | 76.5 | 70.9 | 64.0 | 54.1 | x | 74.9 | 69.6 | 70.1 | |
| *Ammonia parkinsoniana* (d'Orbigny, 1839) | | | | | | | | | | | | 5.4 | 4.7 | x |
| *Ammoscalaria runiana* (Heron-Allen & Earland, 1916) | | | | | | 1.6 | 0.9 | 0.6 | | | 0.3 | 1.4 | | |
| *Aubignyna perlucida* (Heron-Allen & Earland, 1913) | | 0.5 | 4.2 | | 4.1 | 8.5 | 15.9 | 18.1 | 28.4 | | 15.6 | 6.2 | 7.6 | |
| *Cribroelphidium decipiens* (Costa, 1856) | | | | | | 1.6 | 1.9 | 4.8 | 6.3 | | 0.3 | 0.9 | 7.2 | |
| *Elphidium granosum* (d'Orbigny, 1846) | | | 16.5 | | 11.8 | 1.1 | 1.0 | 2.9 | 2.5 | | 1.6 | | | |
| *Elphidium complanatum* (d'Orbigny, 1839) | | | | | | | | | | | | 0.6 | 4.4 | |
| *Elphidium cuvilleri* Lévy, 1966 | | 0.3 | | 0.9 | 2.6 | 1.3 | 3.7 | 3.8 | 6.2 | x | 1.6 | 3.8 | 2.8 | |
| *Elphidium macellum* (Fichtel & Moll, 1798) | | | | | | | | | | | | 0.3 | | |
| *Massilina disciformis* (Williamson, 1858) | | | | | | | | | | | | 1.9 | | |
| *Massilina gualteriana* (d'Orbigny, 1839) | | | | | | | | | | | | 1.7 | | |
| *Massilina secans* (d'Orbigny, 1826) | | | | | | | | | | | | 3.3 | | |
| *Protelphidium anglicum* Murray, 1965 | | 3.8 | 10.0 | 4.0 | 20.5 | 8.1 | 5.7 | 5.8 | 2.5 | | 5.2 | | 3.2 | |
| *Quinqueloculina oblonga* (Montagu, 1803) | | | | | | | | | | | | 0.4 | | |
| *Trochammina inflata* (Montagu, 1808) | | | | 0.8 | | 1.3 | | | | | 0.5 | 0.7 | | |

Tab. 3 - Distribution of the foraminifers (in alphabetical order); the presence is indicated as percentage. The scattered presence are indicated with x.

rine and fresh-waters inputs. In the interval 4 the only species (*Cyprideis torosa*) recorded is usually indicative of strong fresh-water inputs, although, the bad state of conservation, evidently as the result of a transport process, has leaded us to considerate the latter species allochthonous and in consequence, this core dubiously related to zone 2.

- core 1, on the top, which coincides with interval A1, shows assemblage "c" which indicates zone 1, located near the sea and strongly influenced by marine water incomes.

Summarizing, the stratigraphical sequence of the core shows successive changes which evidence an environmental evolution within a lagoon setting. The oldest interval presents an inner border environment, afterwards it evolves towards intermediate conditions between the sea and the inner borders, then, to conclude the environmental sequence, it progresses into an episode of a lagoon environment very strongly influenced by marine water.

Finally, in all the borehole the absence of displaced fresh-water forms can be underlined. This situation may be normal in the lagoon settings near the sea, where the environment is affected by the marine influence. On the contrary, their absence near the inner border of the lagoon influenced by fresh-water income is a debatable question. The study of the other boreholes will attempt to explain focusing on possible link to well defined climatic conditions or peculiar lagoon morphologies.

### Foraminifers.

The foraminiferal analysis evidences several species (Tab. 3) which can be included in three autochthonous assemblages:

Assemblage 1 consists of the combination of the brackish-water *Ammonia beccarii tepida* (presence of 70%) and *Aubignyna perlucida*, together with some other typical marine species such as *Ammonia parkinsoniana*, *Massilina* spp., *Quinqueloculina* spp. and *Elphidium* spp.

Assemblage 2 is characterized by the predominance of *Ammonia beccarii tepida* (presence >50%) and, subordinately, *Aubignyna perlucida* (up to 28%). Other brackish-water species (*Protelphidium anglicum*, *Elphidium granosum*, *Trochammina inflata*) and, occasionally, marine species (*Ammonia parkinsoniana*, *Ammoscalaria runiana*, *Cribroelphidium decipiens* and *Elphidium* spp.) occur in this assemblage, both reaching a presence of about 10%.

Assemblage 3 is conventionally subdivided in two sub-assemblages on the basis of the different percentage presence of the *Ammonia beccarii tepida*:

- the subassemblage 3a is characterized by the high percentage of *Ammonia beccarii tepida* (<70%), together with other brackish-water species (*Protelphidium anglicum*, *Elphidium granosum* and subordinate *Aubignyna perlucida*) which complessively show a presence of about 30%.

- the subassemblage 3b consists of the dominance of *Ammonia beccarii tepida* (presence >90%) and/or by its exclusive presence (core-sample -9.28/-9.26 m deep). Other species occur occasionally in this assemblage: *Protelphidium anglicum*, *Elphidium cuvilleri* and *Aubignyna perlucida*.

In addition, scattered displaced specimens are found in cores A 4 (-3.28/-3.26 m deep) and A 1 (0.23/0.25 m).

All these species are mainly characteristics of lagoon and infralittoral settings as already reported by Carbonel

& Pujos (1982), Vismara Schilling & Ferretti (1987), Albani & Serandrei Barbero (1990), Sgarrella & Moncharmont Zei (1993); some of them are represented in Pl. 2.

Considering the composition of the assemblages, the predominance of brackish-water species together with the subordinate presence of marine ones may indicate a sea-water influenced lagoon environment. Thus, assemblages 1 and 2 can be related to lagoon environment with sea water incomes, meanwhile assemblage 3 can be related to lagoon environment.

Focusing on the presence of some species in the assemblages, this environmental interpretation can be refined.

Assemblage 1, which presents typical marine species (miliolids and other rotaliids), indicates an environment evidently influenced by sea-water. Assemblage 2, which shows the highest percentage of *Aubygnina perlucida* with respect to other assemblages, testifies lagoon settings with elevated water circulation in agreement to the observations of Vismara Schilling & Ferretti (1987), in the S. Teodoro Lagoon (Sardinia), and Albani & Serandrei Barbero (1990), in the Venice Lagoon. Subassemblage 3a, which presents a significative occurrence of *Elphidium granosum*, indicate an hypohalyne lagoon in agreement with Albani & Serandrei Barbero (1990).

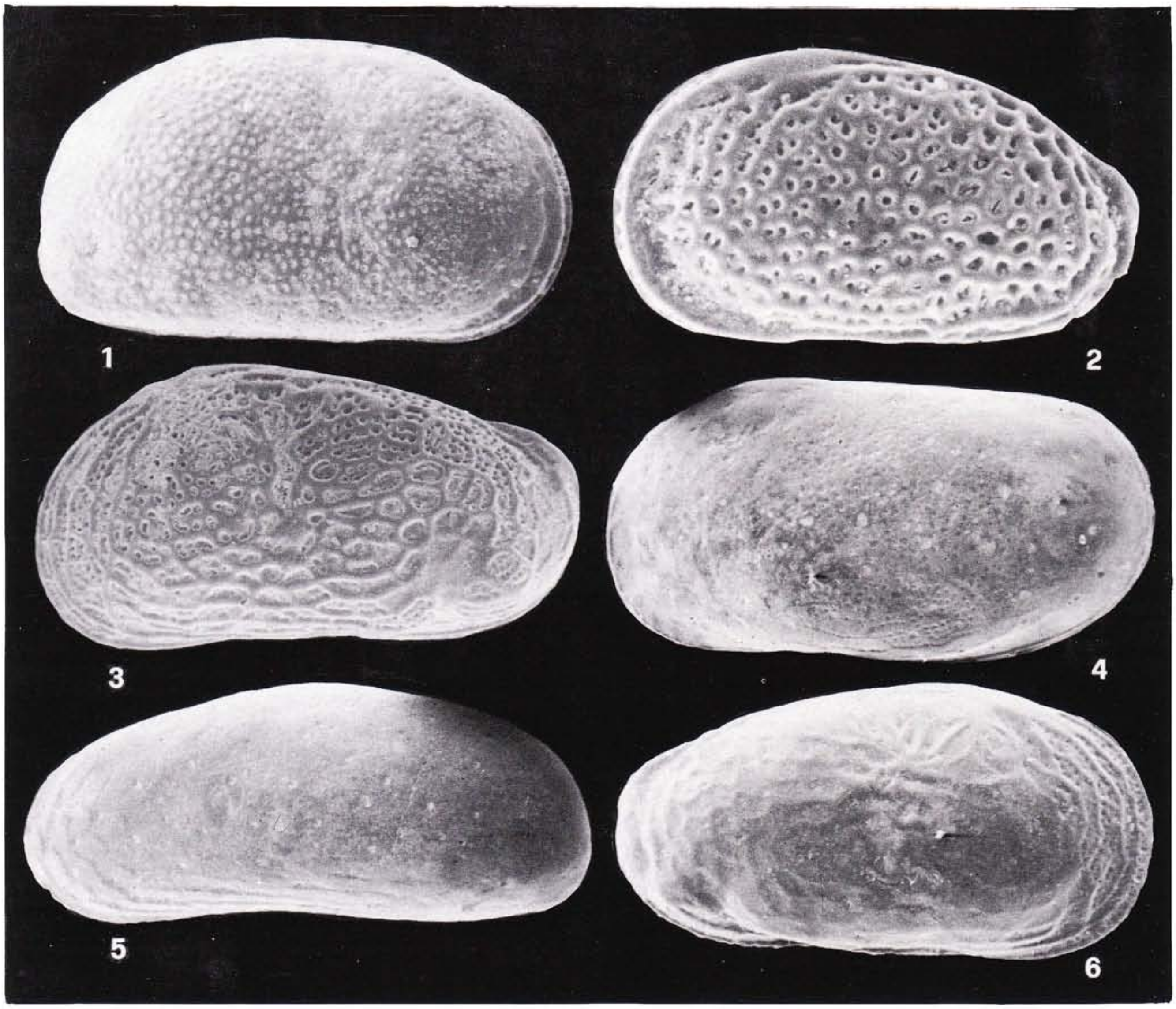

PLATE 1

S.E.M. micrographs of ostracods:

Fig. 1 - *Cyprideis torosa*, right valve in lateral exterior view; x 95.
Fig. 2 - *Leptocythere bacescoi*, left valve in lateral exterior view; x 195.
Fig. 3 - *Leptocythere bituberculata*, left valve in lateral exterior view; x 180.
Fig. 4 - *Loxoconcha elliptica*, left valve in lateral exterior view; x 160.
Fig. 5 - *Pontocythere turbida*, left valve in lateral exterior view; x 90.
Fig. 6 - Leptocytherid sp. 1, right valve in lateral exterior view; x 175.

Subassemblage 3b is characterized by the dominance of *Ammonia beccarii tepida*, characterized by specimens showing a very open umbilical side (see Pl. 2, fig. 1). The latter specimens are described as morphotypes "a" by Carbonel & Pujos (1982) and considered as markers of a scarcely oxygenated environment.

Summarizing, in the borehole assemblage 1 and 2 can indicate the biotope 1 (lagoon influenced by sea-water) and biotope 2 (lagoon with elevated water circulation). The subassemblages 3a and 3b indicate the biotope 3a (hypohalyne lagoon) and 3b (scarcely oxygenated lagoon).

The analysis of all the samples in the cores allows to hypothesize the following environmental evolution:

- from 10 to 8 cores: oscillations of hypohalyne lagoon (biotope 3a) and scarsely oxygenated lagoon (biotope 3b);
- from 7 to 4 cores: lagoon with elevated water circulation (biotope 2);
- from cores 3 to 2: lagoon with evident marine influence (biotope 1).

## Chronostratigraphy.

The radiocarbon data, which have been accomplished on the brackish-water *Cerastoderma glaucum* and peaty materials (*Cymodocea nodosa*), are reported on Tab. 4 and Fig. 4.

| Sample (Laboratory no.) | Material | Depth (m below MSL) | Conventional age (yrs BP) | Calibrated age* (yrs BP) | | |
|---|---|---|---|---|---|---|
| | | | | max | mean | min |
| 4209 | shell | -1.16 | 2355+/-120 | 2111 | 1953 | 1823 |
| 4247 | o.m. | -3.19 | 5515+/-270 | 6195 | 5894 | 5595 |
| 4238 | o.m. | -6.04 | 6270+/-515 | 7254 | 6716 | 6174 |
| 4207 | o.m. | -7.78 | 8060+/-655 | 9365 | 8448 | 7818 |

* The statistic error of the data is 1 standard deviation (1s).

Tab. 4 - $^{14}$C age determination of shell and organic matters taken in borehole A (Valle Vecchia Littoral).

On the basis of the paleoenvironmental interpretation derived from sedimentological, paleontological and micropaleontological data, the deposits of intervals A1 have been originated in lagoon environments in continuity of sedimentation. Thus, considering the calibrated ages, the Caorle paleolagoon already existed from at least Boreal and persisted at the same site up to date when it was reclaimed.

During this time-span the sedimentation rate has ranged as follows: 1.0 mm/yr (from Boreal to Atlantic), 3.5 mm/yr (Atlantic) and 0.5 mm/yr (SubBoreal - SubAtlantic). Such values might be confirmed by the possible age of the soil at -0.14 m below M.S.L. (see Fig. 4). This soil might be originated by recent reclamations: if the sedimentation rate of 0.5 mm/yr was constant, the age of the soil corresponds exactly to the reclamation age (1968 ca).

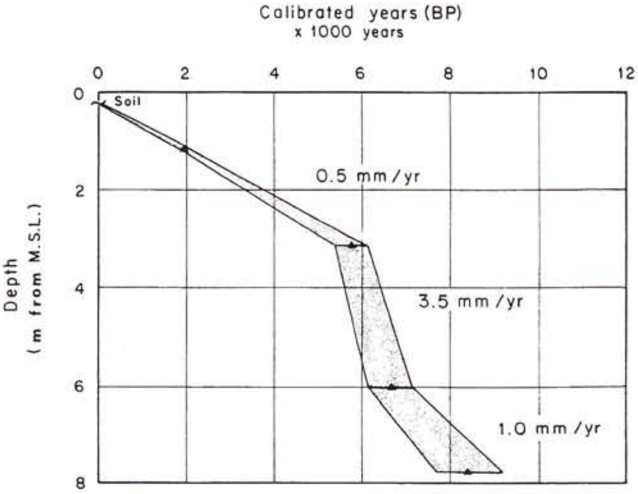

Fig. 4 - Comparison between core-depth and radiocarbon age in Valle Vecchia littoral subsoil. The sedimentation rates are also reported.

Thus, the lagoon environment of Caorle maintained for a longtime a near-balanced equilibrium among relative sea-level rise (subsidence + eustatism) and sediment accumulation rate, producing a feeble progradation trend of the lagoon border. This trend was recently interrupted by a quick reclamation of the old lagoon bottoms. Consequently, beach sands covered the back plain showing a sedimentation rate 10 times higher than those typical of the lagoon.

## Discussion and conclusion.

Several scientific disciplines converge on the multidisciplinar and interdisciplinar research realized on the borehole A. Through this method of analyses an elevated probability to obtain a high level of sharpness in the paleoenvironmental interpretations is reached. In this work the convergence of sedimentological, mineralogical, paleontological, micropaleontological and radiocarbon data have lead the results to a refined paleoenvironmental interpretation of the examined littoral area.

Each discipline gave the proper environmental hypothesis, furthermore, all the environmental proposals were compared among them to verify the coincidences and the divergences, with the aim to obtain a final environmental description in accordance to all the participating specialists. The results of every single speciality are described below.

The sedimentological and mineralogical data have determined a sequence of lagoon environments along the borehole deposits. The lithofacies analyses only gave the possibility to describe a mud flat of a microtidal lagoon environment. Nonetheless, realizing paleontological and micropaleontological investigations by performing autoecological analyses on mollusc, ostracod and foraminiferal fauna, have been obtained the necessary data to verify and refine this interpretation.

Through the mollusc analyses, following the hypothesis of Guelorget & Perthuisot (1983) on the importance of confinement in the zonal distribution of organisms in the paralic environments, two well defined zones (III, IV) and a transitional area (III/IV), all of them in lagoon environment, have been identified.

Ostracod analyses highlight three sea-to-land zones: zone 1, located near the sea and strongly influenced by the marine water incomes; zone 2 related to some areas of the lagoon affected by both, marine and fresh-waters inputs; zone 3, regarding to settings characterized by elevated fresh water inputs, defines environments usually located near the internal borders of the lagoon.

Analyses realized on foraminifera provide three sea-to-land biotopes: biotope 1 determines a lagoon area with elevated marine influence; biotope 3 shows a differentiation on 3a) hypohalyne environment and 3b) anoxic environment; the biotope 2 presents intermediate conditions between biotope 1 and biotope 3a).

The interpretations outcoming from the analyses of every single taxon, notwithstanding corresponding to precise environmental conditions, might not be related

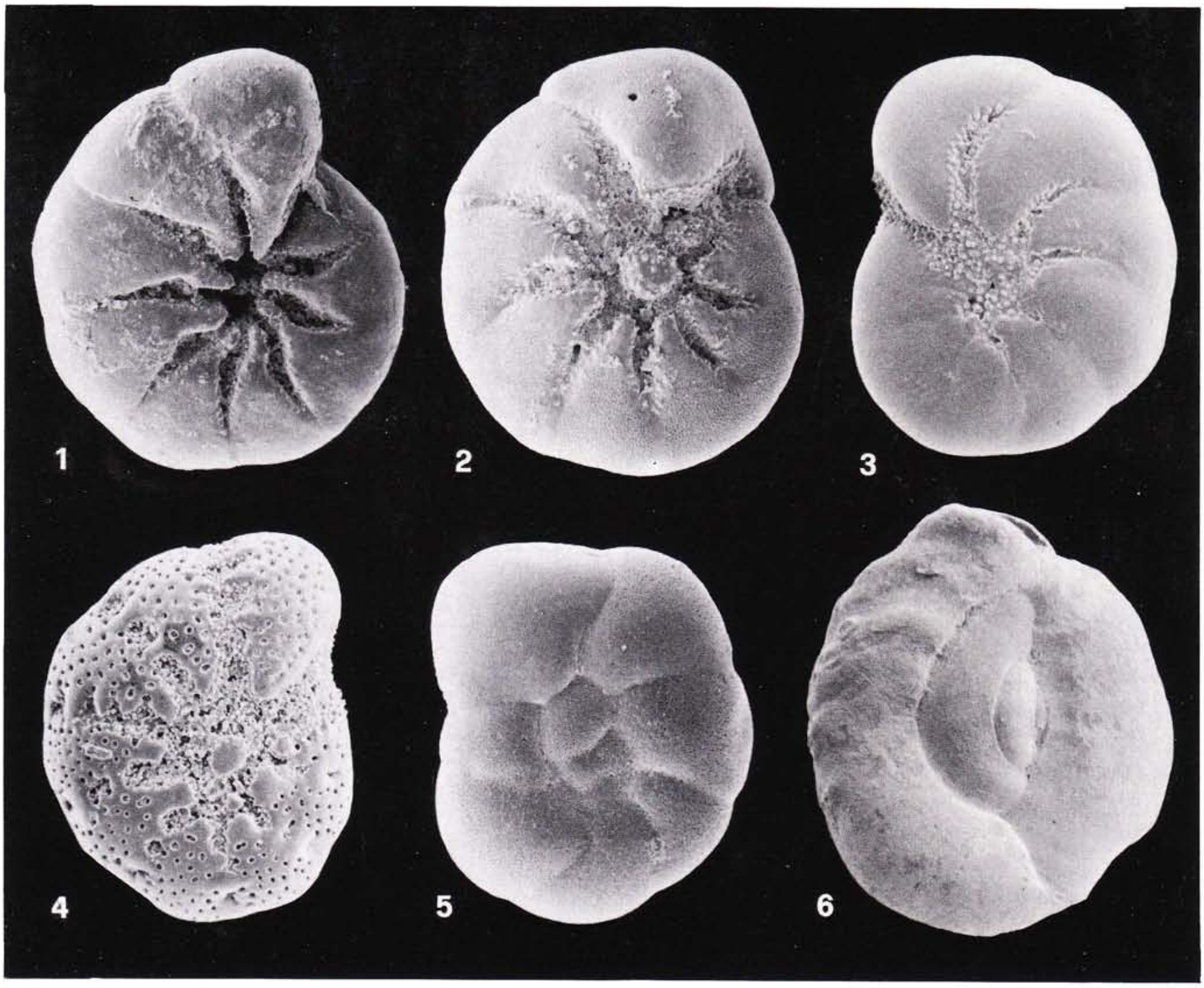

PLATE 2

S.E.M. micrographs of foraminifers:

Fig. 1 - *Ammonia tepida beccarii*, umbilical side; x 130.
Fig. 2 - *Ammonia parkinsoniana*, umbilical side; x 180.
Fig. 3 - *Protelphidium anglicum*, side view; x 175.
Fig. 4 - *Elphidium granosum*, side view; x 210.
Fig. 5 - *Aubignyna perlucida*, side view; x 130.
Fig. 6 - *Massilina secans*, side view; x 50.

to the same zonal organization. Actually, the eventual lack of convergence of the environmental interpretations could reflect local situations. Thus, the paleoenvironmental interpretation is certainly reliable when all the different disciplines coincide in the same environmental conditions.

Following the latter criterion and through the conjunction of the multidisciplinary and interdisciplinar analyses, it have been possible to establish, in the borehole A, three different zones within a lagoon environment: "outer" lagoon, which comprehends the areas of the lagoon located near the sea, obviously showing elevated inputs of marine waters; "central" lagoon, with intermediate conditions between strong marine influence and elevated fresh-water inputs; and "inner" lagoon which presents characteristic relevant fresh-water influence and is usually located along the inner borders of the lagoon. Intermediate conditions between two contiguous zones have also been found.

The environmental sequence, from the lowest interval toward the upper one, evolves as follows:

- on the lower part of the core 10 all the interpretations converge to define inner lagoon;

- from the upper part of core 10 to core 8 included, the analyses coincide assuming inner-central lagoon environments; on the cores 9 and 8, the foraminiferal results have been decisive to refine the environmental interpretation and define the inner connotation within the central lagoon setting.

- cores 7,6,5 and 4 clearly show, through all the analyses, central lagoon environment;

- cores 3 and 2 determine central-outer lagoon; the assumption for outer areas within the central lagoon is supported by the mollusc analyses on core 3 and by foraminifera analyses on core 2; ostracod analyses define central lagoon;

- core 1, the last one, evidences outer lagoon; ostracod records were decisive to define this interval.

Radiocarbon analyses allows to situate the environmental interpretations in a holocenic context.

Figure 3 displays the results of every single discipline involved on the research and the environmental interpretation deduced from the interdisciplinar method utilized to accomplish the whole research.

It seems then to be clear, from the conclusive interdisciplinar paleoenvironmental interpretation, a persistence of lagoon environments in the whole borehole A from at least Boreal up to the moment in which it was reclaimed, nowadays. Within such evolutionary trend, some oscillatory episodes of increased marine influence have been recorded at the lowermost and uppermost parts of the borehole, probably linked to feeble retrogradation of the lagoon borders.

The accumulation rates of the lagoon deposits vary as follows: 1.0 mm/yr (from Boreal to Atlantic), 3.5 mm/yr (Atlantic) and 0.5 mm/yr (SubBoreal -SubAtlantic). Thus, the mean value of the development of Caorle Lagoon bottoms is 1.0 mm/yr. Confronting this data with the data recorded on other lagoons of the area substantial differences are evident: the values of Marano are 1.2-1.8 mm/yr, mean=1.5 mm/yr (Marocco, 1989, reviewed) and Venice ones are about 1.3 mm/yr (Bortolami et al., 1977). These lagoons present different ages: at least 9000 years for the Caorle Lagoon and 5400-5500 years for the Marano and Venice lagoons (Marocco, 1991).

The Caorle Lagoon might be the oldest within the system of the northern Adriatic lagoons, even if Tosi (1994) recognizes lagoon deposits in the southern sector of the Venice Lagoon at a depth of 20-22 m from M.S.L. (conventional age: 10.000 yrs B.P.). However, coeval lagoons are found in Piran Bay (Slovenia) at a depth of 26.5 m below M.S.L. (Ogorelec et al., 1981) and in the offshore of Ravenna (Italy) at a depth of 35-40 m from M.S.L. (Colantoni et al., 1990). Comparing such data and assuming the same sea-level rise for the whole area, it appears evident that subsidence and coastal progradation have certainly played a leading rôle in the control of the recent evolution of the different paralic systems within the northern Adriatic littoral. Consequently, it becomes indeed impossible to propose the same evolutionary model for all the lagoons of the northern Adriatic Sea.

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