Holocene Evolution of the Caorle Barrier-Lagoon (Northern Adriatic Sea, Italy)

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Riassunto. Dati litostatigraphici, paleoecologici e cronostatigraphici ottenuti dallo studio del sondaggio A (10 m di profondità) 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 chronostatigraphical 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 fauna (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 choked 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 continuous-coring boreholes have been drilled along a N-S transect, from Porto Grasso 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 (¹³C) in order to reconstruct the chronostratigraphic and paleo-environmental 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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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 tetrabromomethane (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 organogenus levels. The samples were washed through sieves of 500 and 62 μm. The corresponding washing residues were studied to define molluscs and microfauna (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).
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 (-0.40/-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 stratified 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 peudogley 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 stratified medium-fine grayish brown (2.5 Y 5/2) sands. Topward, abundant and bad-pressed molluscs are present; at the bottom, pelite lumps, carbonaceous 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

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Fig. 3 - Log of borehole A, showing the sedimentological, mineralogical, paleontological, micropaleontological, paleoenvironmental and chronological results.
very common in brackish-water settings (Abra segmentum, Cerastoderma glaucum, Heleobia stagnorum, Hydrobia acuta, Loripes lacteus, Patricardium exiguum, Scrobicularia plana and Ventrosia ventrosa). Following Péres & Picard (1964), the stocks Abra segmentum/Cerastoderma glaucum/Scrobicularia plana and Loripes lacteus/Patricardium exiguum can be included in LEE (Laguine Eurytherme Euryhaline) 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 (Alcoania semistriata, Bittium reticulatum, Bittium scabra, Gibbula adriatica, Pusillina marginata) (Péres & Picard, 1964).

Guelorget & Perthuisot (1983) proposed a zonal distribution of the para-taxa in the lagoon environments based on the concept of confinement. Within the para-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, Myella 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 input (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.
Assemblage "a". This assemblage consists of Cyprides torosa (Pl. 1, fig. 1), Leptocythere baccasci (Pl. 1, fig. 2), Leptocythere ramosa, Loxoconcha elliptica (Pl. 1, fig. 3), Leptocythere lagunae and Loxoconcha stellifera. The combination of typical brackish-water species (Cyprides torosa, Loxoconcha elliptica, Leptocythere lagunae and Loxoconcha stellifera) together with some other species characteristic of marine coastal settings (Leptocythere baccasci and Leptocythere ramosa) indicates brackish-water environment with relevant marine influence. The presence of scattered displaced marine forms, including Cypridocythere (Hölttermannicythere) turbida, Pontocythere turbida (Pl. 1, fig. 5) and Propontocypris sp., validates this interpretation.

Assemblage "b". The second assemblage consists of Cyprides 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 (Cyprides torosa) are simultaneously recorded. The coincidence of sporadic autochthonous Pontocythere turbida and displaced Cyprides 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:
1. core 10 shows the presence of assemblage "b", characteristic of zone 3, which determines lagoon environments located near the internal borders.
2. 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-
rines and fresh-water 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 dubious 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 raniana, 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 compositely 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 cucullii and Aubignyna perlucida.

In addition, scattered displaced specimens are found in cores A 4 (-9.28/-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 Aubynina perluclidula 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 hypohaline lagoon in agreement with Albani & Serandrei Barbero (1990).
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 & Puigó (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 (hypohaline 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 hypohaline lagoon (biotope 3a) and scarcely 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.

**Tab. 4** - 

<table>
<thead>
<tr>
<th>Sample</th>
<th>Material</th>
<th>Depth (m below MSL)</th>
<th>Conventional age yrs BP</th>
<th>Calibrated age yrs BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>4209</td>
<td>shell</td>
<td>-1.16</td>
<td>2355±/120</td>
<td>2111 1953 1823</td>
</tr>
<tr>
<td>4247</td>
<td>o.m.</td>
<td>-3.19</td>
<td>5515±/270</td>
<td>6195 5894 5595</td>
</tr>
<tr>
<td>4238</td>
<td>o.m.</td>
<td>-6.04</td>
<td>8270±/515</td>
<td>7254 6716 6174</td>
</tr>
<tr>
<td>4207</td>
<td>o.m.</td>
<td>-7.78</td>
<td>8060±/655</td>
<td>9365 8448 7818</td>
</tr>
</tbody>
</table>

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

**Discussion and conclusion.**

Several scientific disciplines converge on the multidisciplinary and interdisciplinary 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, palaeontological, 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 paleontolo-
gical 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 freshwaters 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 coming from the analyses of every single taxon, notwithstanding corresponding to precise environmental conditions, might not be related

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 interdisciplinary analyses, it has 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-outter 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; ostracods 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 in the research and the environmental interpretation deduced from the interdisciplinary method utilized to accomplish the whole research.

It seems then to be clear, from the conclusive interdisciplinary 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. (Gorelec 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 role 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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