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Earth-Science Reviews 72 (2005) 89–111

EARTH-SCIENCE REVIEWS

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Marine and brackish-water ostracods as sentinels of anthropogenic impacts

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Received 22 January 2005; accepted 4 May 2005

Abstract

This review analyses the ostracod responses to pollution-induced environmental changes by anthropogenic impacts. Different biological features such as the variability of the local assemblages, population density, species diversity, age population structure and polymorphism, coupled with the favourable results of recently developed bioassays, suggest that these microorganisms may be included between the most promising sentinel groups in both brackish and marine areas. In meiofaunal studies, these microcrustaceans show high sensitivity to heavy-metal pollution, oil discharges and anoxic conditions. In specific investigations based on surveys of recent populations or stratigraphic box-core analysis, both ostracod densities and species diversities decrease remarkably near sources of pollution after a period of pollutant discharge, with a lesser impact in distant or protected areas. Strong heavy metal pollution or frequent oil spills may cause the disappearance of these organisms or a strong reduction in the number of individuals in a relatively short time period, whereas total or partially untreated urban wastes or agricultural discharges causing eutrophication effects lead to the dominance of distinctive species that are adapted to hypoxic conditions.

The environmental improvement derived from the recent implementation of legal regulations in some countries has also been documented in the changes in ostracod assemblages back to pre-disturbed conditions. In addition to population and community changes, morphological and geochemical changes can also be detected in the ostracod carapace, which serves as a tracer of the water quality during the moulting processes.

Keywords: ostracod; anthropogenic impact; waste; brackish; marine environments

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doi:10.1016/j.earscirev.2005.04.003

1. Introduction

In many coastal and nearshore marine areas, human activities introduce distinctive pollutants whose introduction into the natural environment can produce severe alterations in the different trophic levels of the ecosystems. In the last few decades, an increasing number of investigations have been focussed on the search for organisms that serve as a means of monitoring biologically the impact of anthropogenic changes in these environments. For example, some general models were proposed connecting the occurrence of the faunas with the degree of eutrophication (i.e., Fig. 1; Kitamori, 1984; Orive et al., 2002), whereas other more specific investigations have focused on the impact of selected consequences of this eutrophication in ecosystem functioning (i.e., hypoxia; Diaz and Rosenberg, 1995; Gray et al., 2002).

Among macrofaunal organisms used in biomonitoring, both communities and individual species of bivalves (Cossa, 1995; Hiss et al., 1999), echinoderms (Fernández and Beiras, 2001; Beiras et al., 2003), sponges (Pérez et al., 2003), anemones (Harland et al., 1990), crustaceans (Rainbow and White, 1989; Clason et al., 2003) and fishes (Kress et al., 1998; Ueno et al., 2002) have usually been used as bioindicators or biomonitors (see Rinderhagen et al., 2000 for distinction) for this purpose.

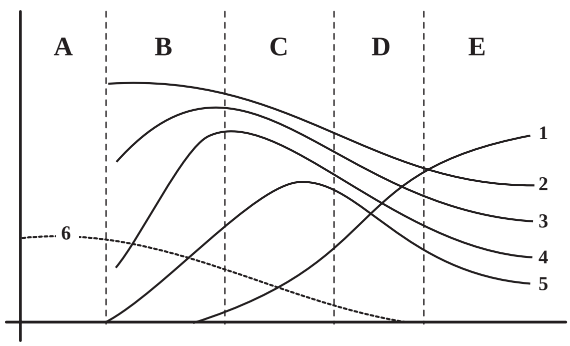

Fig. 1. Occurrence of the different benthonic faunas in relation to the degree of eutrophication (modified from Kitamori, 1984). (A) Azoic area; (B) polluted area; (C) over-trophic area; (D) eutrophic area; (E) normal marine area; (1) percentage of Crustacea; (2) percentage of Polychaetes; (3) number of individuals/number of species; (4) number of individuals; (5) number of species; (6) amount of contaminants in sediments.

In addition, other meiofaunal biomarkers permit the evaluation of the effects of anthropogenic impacts. Some examples include harpacticoid copepods (Lampadariou et al., 1997; Lee et al., 2001), turbellarians (Lee and Correa, 2005), foraminifers (Alve, 1995; Yanko et al., 1999), diatoms (Cooper and Brush, 1991) and dinoflagellate cyst (Willard et al., 2003). Ostracods are another meiofaunal group with increasing uses as biomonitors of stressed conditions in recent and Quaternary environments (Malard et al., 1996; Mosslacher, 2000; Anadon et al., 2002; Boomer and Eisenhauer, 2002).

This review attempts to analyse the potential of ostracods as possible tracers of changes produced by human-induced activities in order to evaluate its use in the resolution of environmental problems in coastal and marine areas of the world (Fig. 2). The main objective is to examine the effects of different anthropogenic impacts on the densities and diversities of the ostracod assemblages, the abundance and distribution of selected species and the chemistry of its carapace. Results can be applied to palaeoecological interpretations (i.e., time-series analysis of the influence of anthropogenic impacts on ostracodes) using sediment cores, and such palaeoecological studies are also reviewed in this paper.

2. The advantages of ostracods

2.1. Main features

Ostracods are microcrustaceans with a bivalve carapace composed of low-Mg calcite ($CaCO_3$) that encloses the body of the organisms. Their faunal composition, population density and diversity are variable spatially and temporally depending on various environmental factors (e.g., water temperature, salinity, water depth, grain size, anthropogenic impacts). Ostracods grow by moulting (eight instars in most cases), with a total regeneration of the whole carapace in some hours to few days (Tétard, 1975). The dominant calcium carbonate, other additional components (Na, Al, K, Fe, S, P) and the secondary trace elements (Cr, Mn, Cu, Zn, As, Sr) obtained from the ambient waters during shell secretion are not stored before the moulting interval (Turpin and

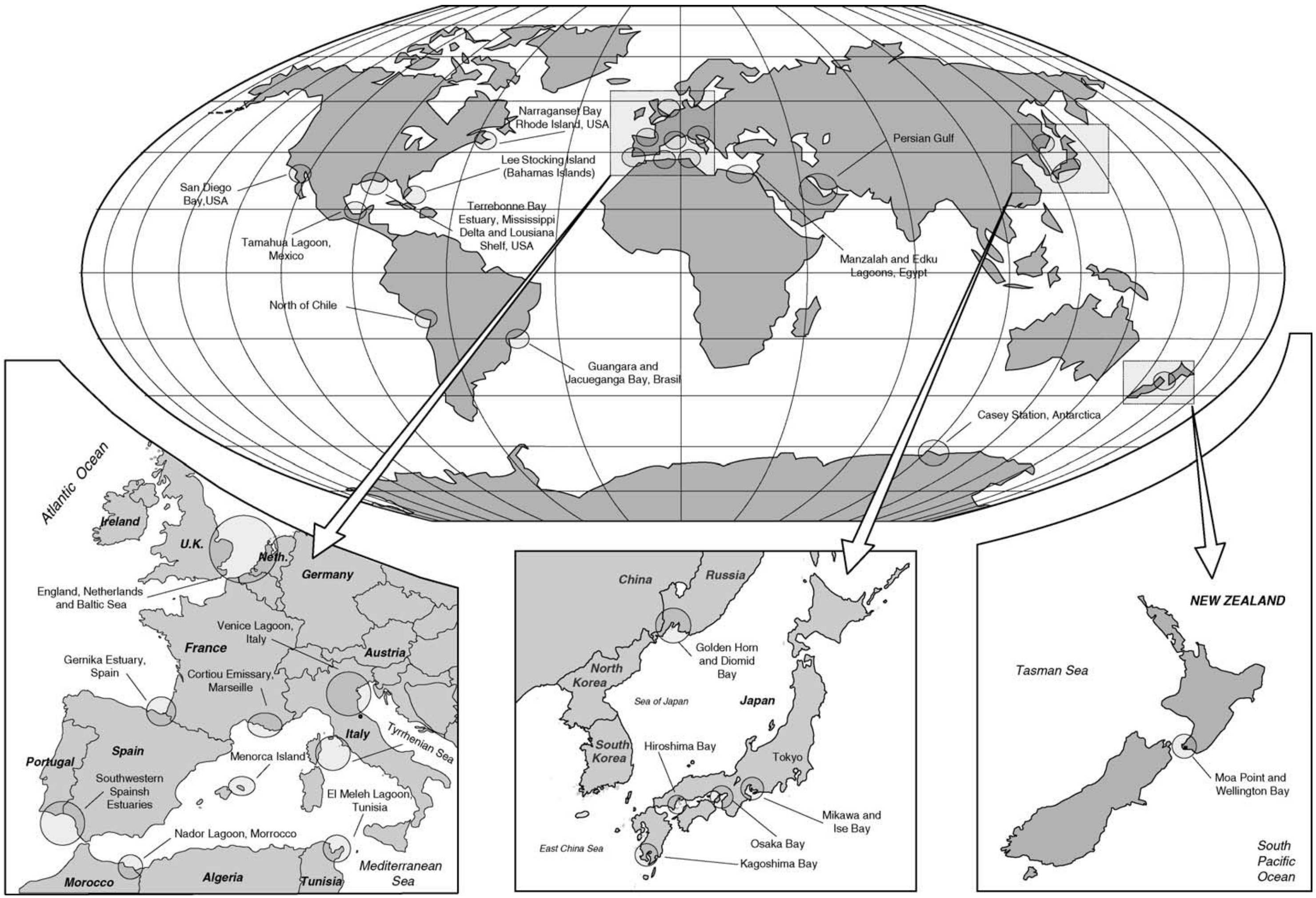

Fig. 2. Main coastal and marine areas of the world used in this work to evaluate the potential of ostracods as possible tracers of changes produced by human-induced activities.

Angell, 1971). Turpin and Angell's (1971) experiments have shown that the whole Ca of the $CaCO_3$ present in the ostracod carapace proceeds from the surrounding waters and is not retained from earlier moults. We can thus consider that it is the same for the chemical elements, which enter to the lattice of the calcite. Bodergat et al. (1991) and Río et al. (1997) showed that the other chemical elements are trapped passively in the shell during moulting.

An inherent potential of this mode of growth is the application of population age structure techniques to the ostracod species and assemblages. For this purpose, it is necessary to determine the percentages of each instar present in the samples studied, in order to analyse the different types of population structure histograms and their interpretations. Although these techniques have been barely used, they present an interesting potential concerning to the determination of abnormal mortalities in the juvenile instars, the modifications of the natural age structure by human development, the response of a species to different bottom current velocities and sediment bypassing or the qualitative analysis of sedimentation rates in petroleum sedimentology (Pokorny, 1965; Oertli, 1970; Whatley, 1988; Irizuki, 1989; Irizuki et al., 1999; Ruiz et al., 1998, 2003). Other biological characteristics (e.g., the ratio of carapaces to valves or right to left valves) have been used also in sedimentological analyses (see Irizuki et al., 1999 and references therein).

On the other hand, life-history strategies of different species can help in the interpretation of the environment (McArthur and Wilson, 1967; Greenslade, 1983). In stable and unpolluted environments, species diversity is high, and mortality of juvenile instars is low (K-strategy). Conversely, diversity is usually low in polluted environments, where both ostracod abundance and mortality rate of juveniles are high (Samir, 2000).

Another interesting feature of ostracods with potential to monitor environmental disturbance is the presence of polymorphism (Fig. 3). The morphological variability of an ostracod species can vary due to changes in environmental variables such as ionic ratios (Carbonel, 1982; Van den Bold, 1990), hydrodynamic levels (Dequan, 1990), the seasonal conditions (Bodergat, 1983; Carbonel et al., 1990; Bodergat et al., 1991) or the physical–chemical equilibrium at the water–sediment interface (Carbonel and Tölderer-Farmer, 1988). One of the most frequent consequences is the presence of different types of reticulation, with diverse morphotypes that respond to the agradation–degradation phenomenon defined by Peypouquet et al. (1987, 1988).

These studies have demonstrated the sensitivity of these organisms to environmental changes and constitute a background whose conclusions can be applied to the fossil record (see Holmes and Chivas, 2002, for a review). The stratigraphical ostracod record is a very fine indicator of historical trends because the ostracods comprise one of the metazoan groups occurring in enough density to enable quantitative assemblage analysis in sediment cores (Cronin and Vann, 2003).

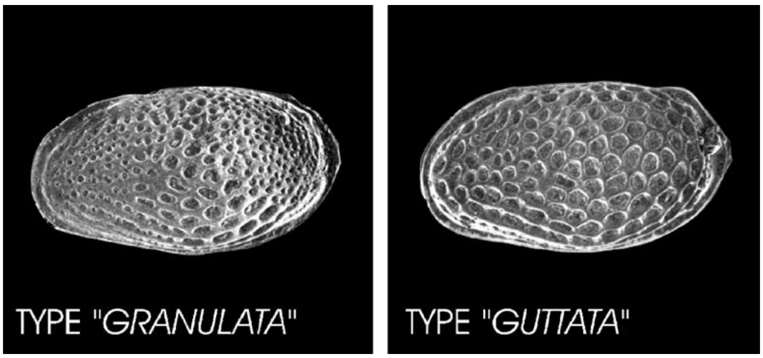

Fig. 3. Polimorphism in specimens of the ostracod *Palmoconcha guttata* (Norman) collected in coastal sediments of Morocco (modified from Carbonel and Hamoudi, 1990).

2.2. Laboratory and field experiments: a further promising approach

2.2.1. Methodology: a critical review

The ostracod faunas of both marine and brackish environments are usually analysed as part of more extensive field bioassays which include other meiofaunal groups, such as nematodes, copepods, polychaetes or kynorhynchs. In these investigations, the two first groups are profusely studied (Moore et al., 1997; Millward et al., 2004) whereas ostracods play a secondary role.

These cases usually involve microcosm experiments realized mainly in brackish environments (salt marshes, estuaries, deltas), where different concentrations of pollutants (hydrocarbons, heavy metals) are added to a subset of subsamples whereas another subset remains unpolluted. Other investigations effectuate a comparison between a set of samples located near a local source of organic or inorganic contaminants and control stations placed out of the pollution influence.

These bioassays have usually a very careful methodology and the spatial densities are tested by statistical techniques applied even to replicated samples or cores. Nevertheless, whereas the ostracod densities are almost always determined, the ostracod diversity is unknown (Mazzola et al., 1999) and consequently it is not possible to determine the key species which may be used as biomonitors or bioindicators. In addition, very scarce field experiments present an adequate statistical analysis between the main environmental variables and the meiofaunal distribution (Dalto and Alburquerque, 2000). Other possible problems are derived from the exclusive use of adults (Ritterhoff and Zauke, 1997), which impedes the evaluation of the ontogenetic changes caused in the ostracod populations by pollutants.

2.2.1.1. Ostracods and oil contamination. After 6 months of treatment, an experiment with effluents from a refinery with cracking processes resulted in low densitites of ostracods in the polluted samples in comparison with the control, whereas increasing number of valves was found after 15 months (Liljenstroem et al., 1987). Similar bioassays (Table 1) have demonstrated that this sensitivity varies between those brackish and marine communities chronically exposed to petroleum hydrocarbons for decades (i.e., Louisiana) and others relatively uncontaminated (i.e., Mississippi). In the latter, ostracods are negatively impacted to a greater extent, with lower abundances in high treatments even on Day 10 after the experiment beginning. On Day 21, ostracod response to diesel fuel differed between sites, whereas the abundance decreased in a dose-dependent fashion in the Mississippi microenvironments (Fig. 4A; Carman et al., 2000).

2.2.1.2. Ostracods and heavy metals. In different manipulative field experiments, arthropods (amphipods, isopods, cumaceans and ostracods), harpacticoid copepods, nematodes and turbellarians respond negatively to metal toxicants. The ostracod response has been tested statistically for copper (with or without co-occurring organic enrichments; Lenihan et al., 2003) and zinc (Watzin and Roscigno, 1997). In this last bioassay, there were always fewer individuals in the Cu–Zn treatments than in the control (Fig. 4B).

This correlation was also found in non-manipulative studies made in northern Chile, where the Cu sediment enrichment due to the disposal of copper mine tailings induces a reduction of both densities and diversities of the meiofaunal assemblages. In this area, ostracods contribute significantly to the dissimilarities between the reference area and the polluted zones (Lee and Correa, 2005).

At Casey Station (Antarctica), ostracods are also included among the most interesting meiofaunal organisms to differentiate the disturbed areas from the control locations, even when selected statistical analyses are applied, such as ANOVA, non-metric multidimensional scaling or analysis of similarity (Stark et al., 2003). This ostracod contribution to the meiofaunal dissimilarity has been also found in the Jacuacanga Bay, Brazil (Dalto and Alburquerque, 2000).

Finally, a comparison between metal and diesel tolerance indicates that these microcrustaceans are “diesel-sensitive” and “metal-resistant” organisms (Fig. 4C; Millward et al., 2004).

2.2.1.3. Ostracods and organic nutrients. The main effect of fish-farm plants is the increase of organic nutrients (proteins, carbohydrates, lipids, ash and cellulose) in bottom sediments derived from the fish food

Table 1
Response of the meiofauna (including ostracods) to different laboratory/microcosms experiences and human-induced environmental problems

Location	Environmental conditions and problems	Consequences on meiofaunal assemblages	Ostracod response	Reference
Santa Barbara, California, USA	Oil seep area	Positive correlation between the amount of oil present and the nematode densities. Negative correlation with polychaetes, gammarids, oligochaetes, bivalves, copepods and cumaceans	Negative correlation with the oil concentrations	Steichen et al., 1996
South West Gales, UK	*Sea Empress* oil spill	Nematode abundance doubled at the heavily oiled site. No significant changes in copepods and turbellarians	No significant changes at the heavily oiled sites	Moore et al., 1997
Ensenada del Pabellon Lagoon, Mexico	Agroindustrial drainages	Lowest meiofaunal densities in stations with sandy sediments with low carbon and nitrogen contents, located further away distant from agroindustrial discharges	Positive effect of high carbon contents on ostracod densities.	Noguera and Hendrickx, 1997
Field experiment, Mobil Bay, USA	Effects of zinc contamination on the benthic invertebrate community	Harpacticoids, nematodes and turbellarians with lower numbers in the zinc treatment than in the control	Low to medium impact (reduction of 10–60% in the ostradoc densities)	Watzin and Roscigno, 1997
Gulf of Riga, Eastern Baltic Sea	Eutrophied area with high annual primary production	Harpacticoids abundant in sediments with moderate LOI (5–10%). Highest nematode abundances in sediments with low organic contents	Number of ostracods higher at stations with low organic contents	Pallo et al., 1998
Gaeta Gulf, Italy	Organic loads due to the biodeposition of a new fish farm	Significant reduction of the total density after only 6 weeks. Disappearance almost complete of kinorhynchs. Significant decrease of nematodes and copepods. Partial recovering 5–7 months after cage disposal	Very high mortality (80–90%)	Mazzola et al., 1999
Manukau Harbour, New Zealand	Discharge of treated sewage wastewater	Total abundance of benthic organisms decreased as a function of distance from the outfall	Moderate tolerance/sensitivity to the contamination gradient	Ellis et al., 2000
Microcosms experiment	Impact of a mixture of Cu, Cr, Cd, Pb and Hg at different concentrations after three time periods	Abundances of deposit feeders (some polychaetes, gastropods and bivalves) stronger impacted than mainly algal feeders (copepods and nematodes)	Ostracod abundance decreased only in the highest metal treatment	Millward et al., 2001
Field experiment, Lagos, Nigeria	Heavy metal pollution by industrial effluents and drainage channels	Hg as the most toxic to all test species followed by Cu, Mn and Fe	*Cypris* sp. as the most tolerant species	Oyewo and Don-Pedro, 2002
Field experiment, McMurdo Station, Antarctica	Response to total organic carbon (TOC) in sediments and copper on colonizing benthos	Arthropods and echinoderms: decrease with Cu and variable response to TOC	Decrease in high organic loading and Cu (included in arthropods)	Lenihan et al., 2003
Casey Station, East Antarctica	Two waste dumps, a sewage outfall and a wharf	Lower species richness and less variable assemblages at disturbed stations	Important contribution to differences between the disturbed and the control locations. *Doloria* sp. more abundant at control locations	Stark et al., 2003
Chañaral area, northern Chile	Copper mine tailings	Lower densities and taxa diversities in the meiofaunal assemblages at the impacted sites	Ostracods as important contributors to the dissimilarity between the reference site and the remaining areas	Lee and Correa, 2005

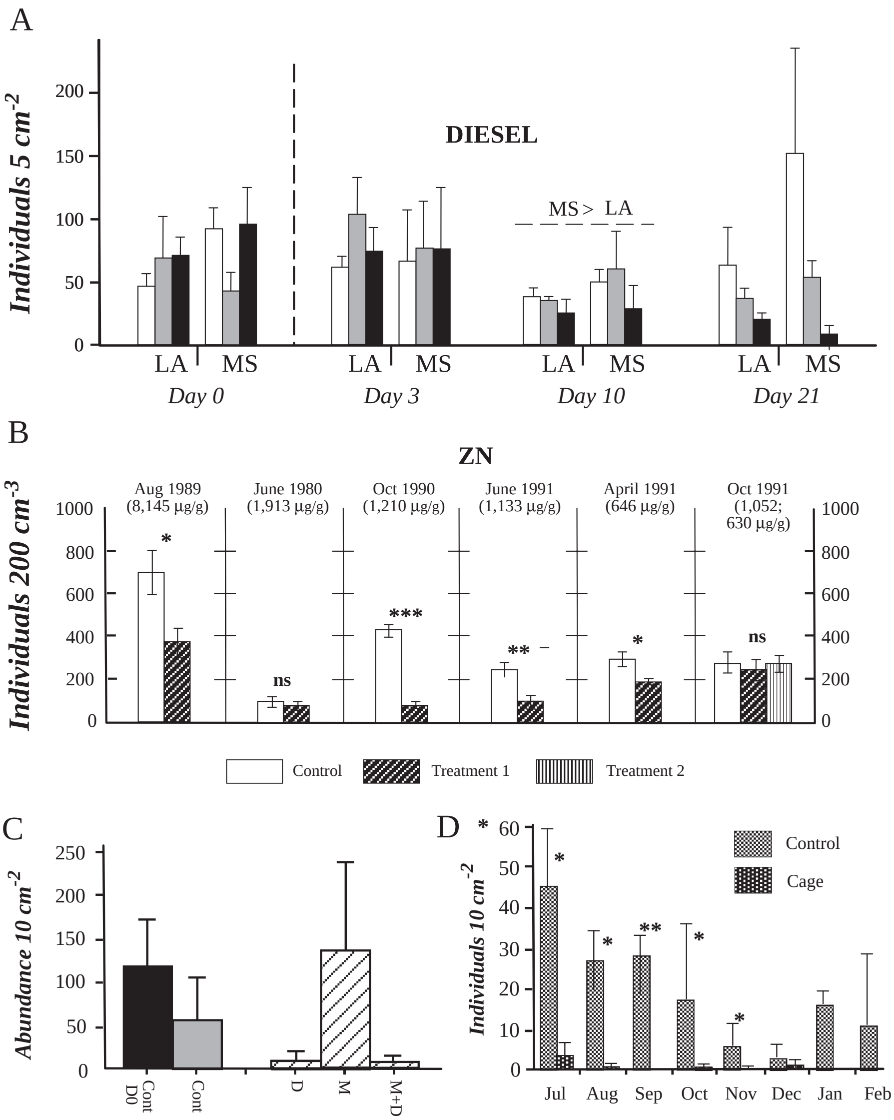

Fig. 4. (A) Abundance of ostracods after different exposure times (Days 0–21) to diesel treatments in Mississippi (MS) and Louisiana (LA) microcosms (modified from Carman et al., 2000) White, control; Grey, medium; Black, high. Values are mean ± 1 S.D. ($n=4$). (B) Abundance of ostracods in Zn-contaminated and control sediment (modified from Watzin and Roscigno, 1997). ns = no significant difference between treatment and control means; * = treatment and control means significantly different at the $p \leq 0.05$ level; ** = treatment and control means significantly different at the $p \leq 0.01$ level; *** = treatment and control means significantly different at the $p \leq 0.001$ level. (C) Ostracod response to mixtures of metals and hydrocarbon (modified from Millward et al., 2004). Treatment were control Day 0 (Cont D0), control Day 30 (Cont), metals (M), diesel (D) and metals + diesel (M + D). Bars represent mean ± 1 S.D. (D) Temporal variations in ostracod densities in the control site and under the cage of a fish farm (modified from Mazzola et al., 1999). * = $p \leq 0.05$; ** = $p \leq 0.01$.

and the presence of anoxic conditions (Handerson et al., 1997). In the Tyrrhenian Sea (western Mediterranean), these conditions caused a strong reduction of the meiofaunal densities beneath the cage of a new fish farm compared to the control sample during the 8 months after the plant installation (Fig. 4D; Mazzola et al., 1999). In the farm sediments, ostracods displayed a significant decrease or even complete disappearance in the first months after farming activities began.

In the Gulf of Riga (eastern Baltic Sea), the number of ostracod was also significantly higher at stations with low organic contents in sediments than at stations with high organic content (LOI > 10%; Pallo et al., 1998). Nevertheless, a positive effect on the ostracod densities of high carbon contents derived from agricultural and industrial discharges has been also observed (Noguera and Hendrickx, 1997).

3. Wastes and ostracods

3.1. Methodology: a critical review

These researches analyse the variations of the ostracod abundance and species diversity in both surface samples and box cores located around different anthropogenic activities (industrial sewages, urban effluents, agriculture) that cause variable impacts on the adjacent areas (Table 2). The most usual problems are revised below.

3.1.1. Surface samples

Ostracods live mainly in the upper 1 cm of the sediment, and most of them are concentrated in the upper 5 mm, i.e., the flocculent layer and the top of the oxidized layer (Ikeya and Shiozaki, 1993). Consequently, a surface sample includes living individuals and dead specimens belonging to a variable number of previous ostracod generations depending on the individual species ontogeny and the local sedimentation ratios. A first problem is derived from the application of the Rose Bengal method to the recognition of the biocoenosis, because numerous empty carapaces and valves are stained owing to the presence of other microorganisms in the carapace surface (Zhou and Zhao, 1999) or the abundant post-mortem closure observed in some genera, such as *Callistocythere* or *Neocytherideis* (Whatley, 1988).

The final result of this procedure is usually a strong dominance of thanatocoenosis over biocoenosis, with a number of living individuals so low (<2–3 individuals per gram in most samples; Whatley et al., 1996; Ruiz et al., 1997a, 2000a) that constraints the determination of the autoecological range of each species and limits a later statistical analysis. In addition, few taphonomic notes have been published and consequently new risks (see Kaesler, 1979 for a review) are assumed when the main conclusions are based almost exclusively in the analysis of the species assemblages obtained by factorial and principal component analyses or the different sample groups derived from cluster analysis.

Another problem is the use of different laboratory procedures that should impede the comparison of results between investigations realized even in very close areas. Some authors determine the number of individuals present in variable volumes (10–3000 cm^3; Bodergat and Ikeya, 1988; Dias-Brito et al., 1988; Ruiz et al., 1997a) or weights (0.5–3000 g; Whatley and Quanhong, 1988; Whatley et al., 1998; Ruiz et al., 2000b) of dry sediment or algae. Moreover, samples are washed through different sieves (63–200 μm in most cases; Rosenfeld, 1979; Van Harten and Droste, 1988; Bodergat et al., 2002).

On the other hand, these investigations present only an instantaneous environmental scenario and do not include usually temporal pre-spill faunal data of the impacted area. Nevertheless, they are important as background for new studies concerning the same areas.

3.1.2. Box cores

This method permits to remove this last inconvenience, but the scarce quantity of sediment collected (usually <50 g per sample) adds new problems. It is very difficult to obtain a representative number of specimens per sample (≥300; Krutak, 1982) for an adequate statistical analysis and consequently some commonest statistical protocols need to be partially (at least) removed. In this case, results can be considered as a graphic development of the initial database before than a main support of the conclusions.

Bioturbation is a major problem in these studies and may invalidate the main results. Consequently, it is desirable to study the sedimentary and organic structures from radiographs of cores as well as from lacquer peels (Ruiz et al., 1997b).

3.2. Ostracods as short-term tracers of industrial activities

Since 1990, different studies have concentrated on the relationship between historical changes in anthropogenic pollution levels and ostracods in sediment cores collected near industrial areas. In the Tinto-

Table 2
Impact of different pollution sources on the ostracod densities, diversities and/or populations of selected species

Location	Pollution source	Some environmental consequences	Ostracod response	Reference
England–Netherlands–Baltic Sea	Phosphogypsum pollution	No data	Genetic deviation from Hardy–Weinberg equilibrium in a local population of *Cyprideis torosa*	Sywula et al., 1995
Southwestern Spanish estuaries	Historical mining, recent industrial and domestic discharges	Strong heavy metal pollution in sediments. Acid waters	Disappearance near the industrial effluents. Low changes in some tidal channels protected by the natural hydrodynamics and/or barrier islands.	Ruiz et al., 1997a, 2000b
Ise and Mikawa Bays, Japan	Domestic and industrial sewages	High eutrophization level. Red tides almost every year during summer	Low diversities near the pollution source	Bodergat et al., 1998
Nador Lagoon, Morocco	Domestic sewage	Low eutrophization	Monospecific populations of *Palmoconcha turbida*. Ratio number of individuals/number of species higher near the domestic waste	Bodergat et al., 1998
Louisiana shelf, USA	Discharge of anthropogenically-increased nutrient loading	High eutrophization level in an extensive area with seasonal chronic hypoxia	Loxoconchidae as indicators of hypoxia. High correlation between the relative abundance of *Locoxoncha* spp. and the amounts of fertilizer applications	Alvarez Zarikian et al., 2000
Moa Point, Wellington, New Zealand	Discharge of a coastal sewer	Water pollution	Variable, with some species particularly sensitive to high levels of pollution, whereas others can tolerate a broader spectrum of conditions	Eagar, 1999
Manzalah Lagoon, Egypt	Untreated industrial, domestic and drainage waters. Agrochemicals (fertilizers and biocides)	Low to moderate heavy metal pollution. Morphological abnormalities in foraminifera	Migration of living individuals towards unpolluted areas. Only juvenile forms of *Cyprideis torosa* near the pollution source	Samir, 2000
Edku Lagoon, Egypt	Untreated agricultural drainage waters	Unappreciable effects	Unappreciable. Normal brackish–freshwater association	Samir, 2000
Venice Lagoon, Italy	Industrial sewage	Low to moderate eutrophization near the Marghera industrial zone	Disappearance in the highest polluted area and the dredged oil channel	Ruiz et al., 2000a
Gernika estuary, Spain	Undifferentiated sewages in restricted basin	Dysaerobic conditions and low to moderate heavy metal contents	Very low densities and diversities	Pascual et al., 2002
Guanabara Bay, Brasil	Domestic and industry sewages	High total organic carbon contents	Stressed area with numerous populations of *Cyprideis* spp. and rare occurrences of other species	Vilela et al., 2003
Hiroshima Bay, Japan	Industrial wastes and Second World War	Low to moderate heavy metal pollution. Eutrophycation and hipoxia	Decrease of densities and simplification of ostracode assemblages. Some species have strong resistance to anthropogenic pollution whereas others are sensitive to this factor	Yasuhara et al., 2003
El Meleh Lagoon, Tunis	Partially untreated domestic sewages	Low salinity and higher nutrient contents	Low densities and diversities	Ruiz et al., 2004b
Osaka Bay	Domestic and industrial wastewaters	Heavy metal pollution, eutrophication, and hypoxia	Ostracode absolute abundance decreased by 90%	Yasuhara and Yamazaki, 2005

Odiel Estuary (southwestern Spain), the coincidence of historical acidic inputs originating in a historical mining, industrial wastes derived from two industrial zones located near the mouth (fertilizers, petroleum by-products and chemicals) and urban effluents caused the disappearance of ostracod species in the main channels located near the discharge points. Nevertheless, some areas protected by barrier islands, salt marshes or the local hydrodynamics of this estuary have suffered these negative effects to a lesser extent, with an increased number of species and individuals even during the period of highest pollution (1960–1985) (Ruiz et al., 1997a,b, 2004a).

This disappearance was also found in the Gernika estuary (southern Bay of Biscay), with only scarce (probably reworked) specimens belonging to coastal species since 1940 (Fig. 5). Sediments deposited during the highest pollution period (1940–1980) to present contain high levels of heavy metals (As, Pb), the maximum occurrence of the foraminifer *Ammonia tepida* morph C and an absence of ostracods (Pascual et al., 2002).

A similar reduction has been reported recently in Hiroshima Bay (Japan), where ostracod densities diminished rapidly and values of equitability increased from 1940 to 1950, coinciding with a rapid increase in the concentrations of heavy metals (Cu, Zn, Pb). These changes were likely caused by the increasing industrialization and the effects of the Second World War in the region and are more pronounced in the higher-polluted areas located in the inner part of the bay (Fig. 6: core H99-0). In this area, some species (i.e., *Callistocythere alata*) were sensitive, whereas *Bicornucythere bisanensis* was strongly resistant to the anthropogenic impact (Yasuhara et al., 2003).

Although some species are partially resistant to industrial pollution, a remarkable impact was found in their population age structure. In the Ise and Mikawa Bays (Japan), the ostracod productivity is lowest where the concentrations of either Zn, Pb, Cr, or Cu are highest. *Cytheromorpha acupunctata*, which is relatively abundant in polluted areas, is more resistant to pollution than the other species (Bodergat and Ikeya, 1988). In Manzalah Lagoon (Egypt), the *Cyprideis torosa* populations are dominated by juvenile instars near the pollution source, whereas all the ontogenic stages are present in nearby low polluted areas. This distribution could indicate either a retardant effect of the adverse environmental conditions on the rate of the growth or the death of numerous instars during ontogenetic development (Samir, 2000). This species seems to be tolerant to stress by industrial sewages (Vilela et al., 2003).

In some of these polluted areas, the implementation of legal regulations (1970–2000) has caused a marked improvement, with a partial recovery of the pre-industrial conditions. In the Odiel estuary (SW Spain), *Loxoconcha elliptica* has colonized again some areas located near the old industrial discharges (Ruiz et al., 2004a), whereas other marine species are living today in low to moderately polluted sediments in the adjacent marine areas, although the richest populations are found normally in the lowest variation intervals for each metal (<200 ppm in most cases; Ruiz, 1994). In the inner part of the Osaka Bay, ostracod absolute abundance decreased by 90% from ca. 1910–1920 to ca. 1960–1970 as a result of the cited Japan's rapid industrial development, coinciding with a rapid increase in both the concentration of various pollutants and the Osaka population. In this latter area, the ostracod abundance has not recovered despite environmental legislation enforced after ca. 1960–1970 (Yasuhara and Yamazaki, 2005).

3.3. Urban wastes

Some cities have environmental programs to monitor the effects of urban discharges on the local marine biota, whereas others discharge their urban wastes directly or with incomplete biological or chemical treatments. These urban wastes are one of the most widespread forms of disturbance affecting brackish or marine ecosystems. The impact on ostracods depends on factors such as the concentration of pollutants, degree of eutrophication, hypoxia or a combination of some of them. The three following examples illustrate the different effects on the ostracod faunas.

3.3.1. Outfall with advanced treatments (San Diego, USA)

The marine ostracod *Euphilomedes carcharodonta* is one of the most abundant taxa collected in Pacific sediments located near the Point Loma ocean outfall. In 2001, this species was particularly

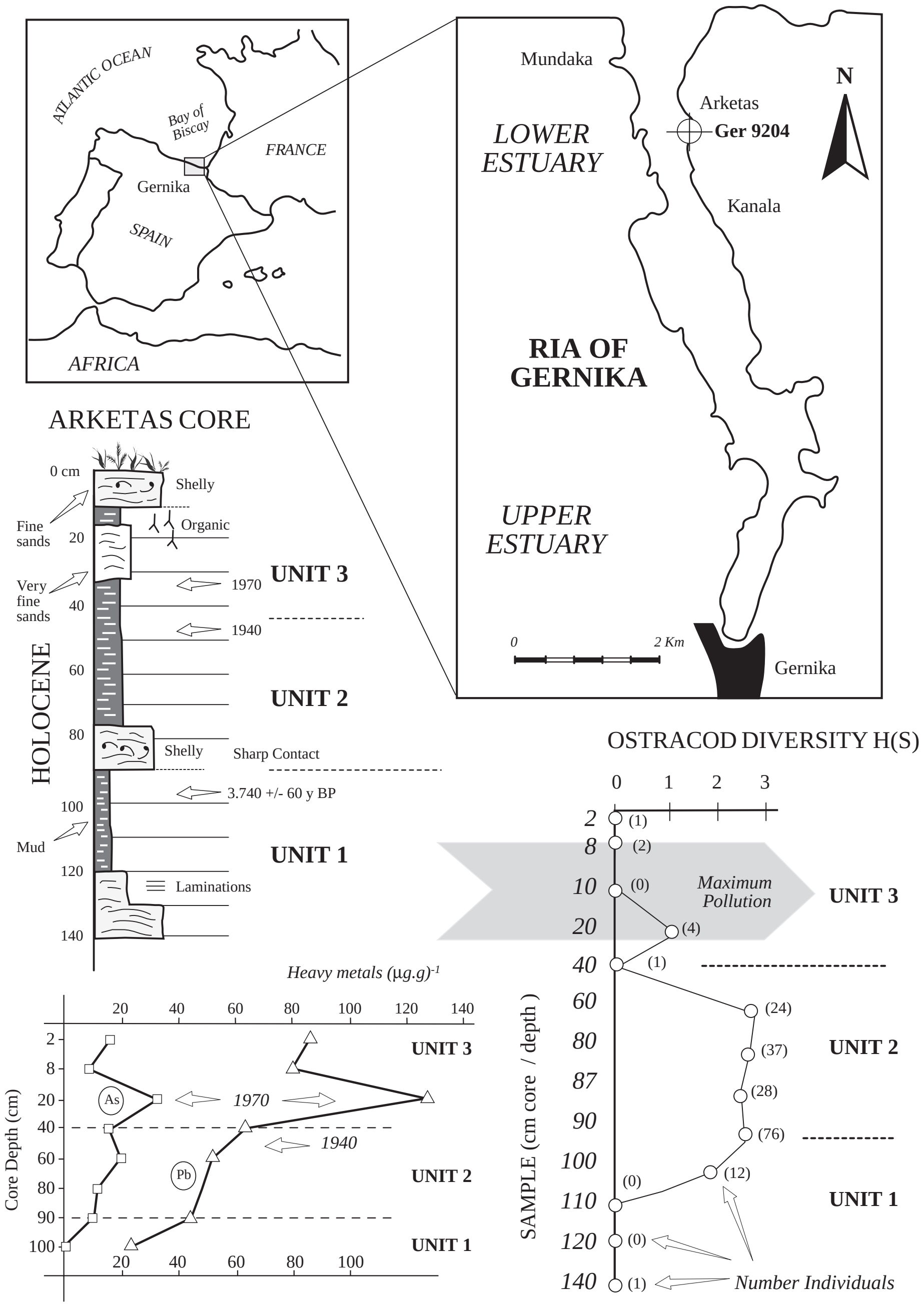

Fig. 5. Location, sedimentology, heavy metal contents and ostracod density and diversity in core Ger-9024, Gernika estuary, northern Spain (data from Pascual et al., 2002).

abundant (mean 39.6 individuals per 0.1 m^2) in those samples collected close to the outfall. In this area, there was an overall increase in the number of species and infaunal abundances since discharge began in October 1993, accompanied by decreases in dominance (City of San Diego, 1995, 1999, 2001). These general patterns are inconsistent with predicted pollution effects and indicate a negligible

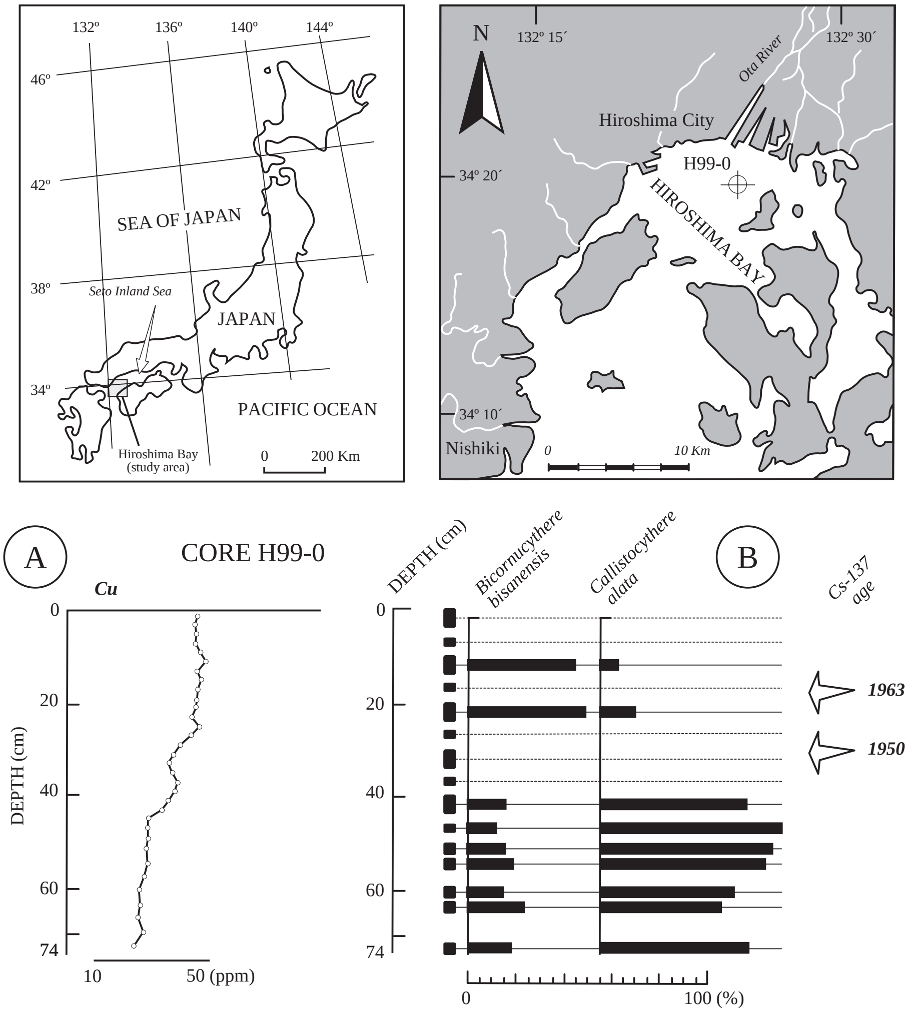

Fig. 6. Sediment core (H99-0) location in the Hiroshima Bay (Japan). (A) Vertical distribution of Cu; (B) vertical changes of the relative abundance of *Callistocythere alata* and *Bicornucythere bisanensis* (modified from Yasuhara et al., 2003). Bars are only applied on the sample horizons that have more than 50 specimens per sample.

effect in the adjacent benthic communities. This result may be due to the application of high levels of wastewater treatment, combined with a secondary treated sewage and an important minimum dilution factor.

3.3.2. Outfall with partial treatment (El Meleh, Tunisia)

El Meleh lagoon (NE Tunisia) receives directly the biologically, non-chemically treated urban waters of Slimene town and adjacent areas. The main effects of the treatment station effluent (3000 m^3 by day) are low salinity and higher concentrations of some nutrients (NO_3^-, HPO_4^-), whereas both waters and sediments present low levels of heavy metals. Near the discharge point (Fig. 7), ostracods are very scarce (5–10 individuals/100 g) in relation to the rest of the lagoon (1500–42,000 individuals/100 g), with the presence of a normal brackish assemblage (*C. torosa*, *L. elliptica*) and the introduction of a new freshwater assemblage (*Ilyocypris*, *Candona*), not observed in subrecent samples. Consequently, salinity changes induced by these inputs may cause a remarkable replacement on ostracod

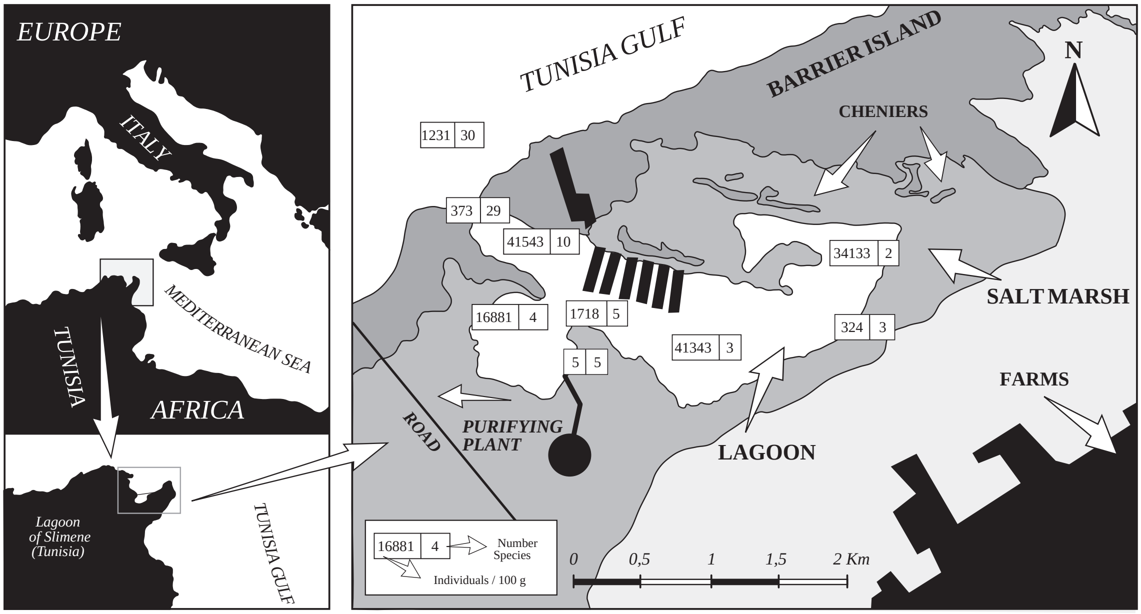

Fig. 7. Number of species and individuals (100 g dry weight) in surface sediments of El Meleh lagoon, Tunis (modified from Ruiz et al., 2004b).

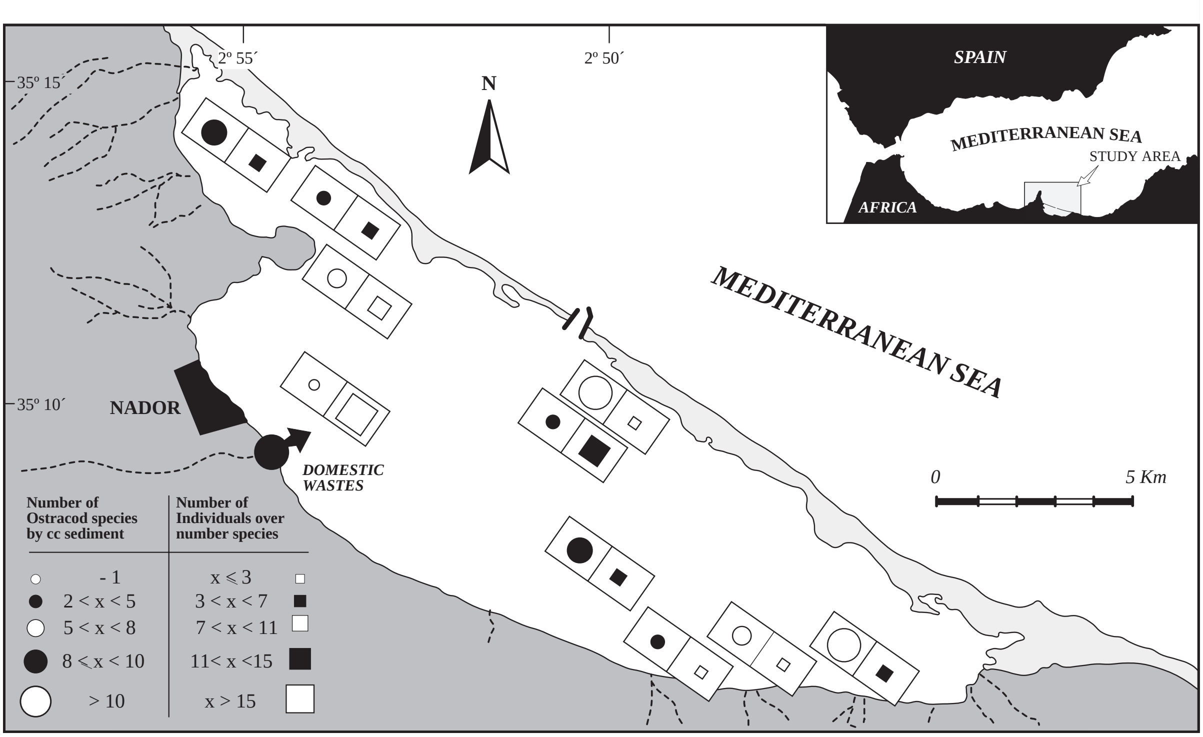

Fig. 8. Ostracod distribution (1978) in the Nador lagoon, Morocco (data from Bodergat et al., 1998).

assemblages related to a major salinity change (Ruiz et al., 2004b).

3.3.3. Outfall without any treatment (Nador, Morocco)

Until 1977, the city of Nador discharged its domestic wastes back to the Nador lagoon. A sampling campaign from 1975 to 1978 showed a very low species richness at stations located in front of city and the adjacent areas (Fig. 8). In this zone, populations were even monospecific, with numerous specimens of the opportunist species (R-strategy) *Palmoconcha turbida* Muller (Bodergat et al., 1998), a species whose tolerance to low oxygen permits its survival in hypoxic environments.

3.4. Agricultural wastes

Few investigations have focussed on the impact of agricultural inputs on the ostracod populations. In the Louisiana inner continental shelf, a seasonal chronic hypoxia is induced by a bigger nutrient-induced productivity as a consequence of the Mississippi River discharges. In this case, the hypoxia tolerance mentioned in the previous sections by some species of the family Loxoconchidae is confirmed, with an increase of the relative abundance of *Loxoconcha* sp. since 1900 within the hypoxic area (Fig. 9). This abundance can be related closely to the amounts of fertilizer application in the United States

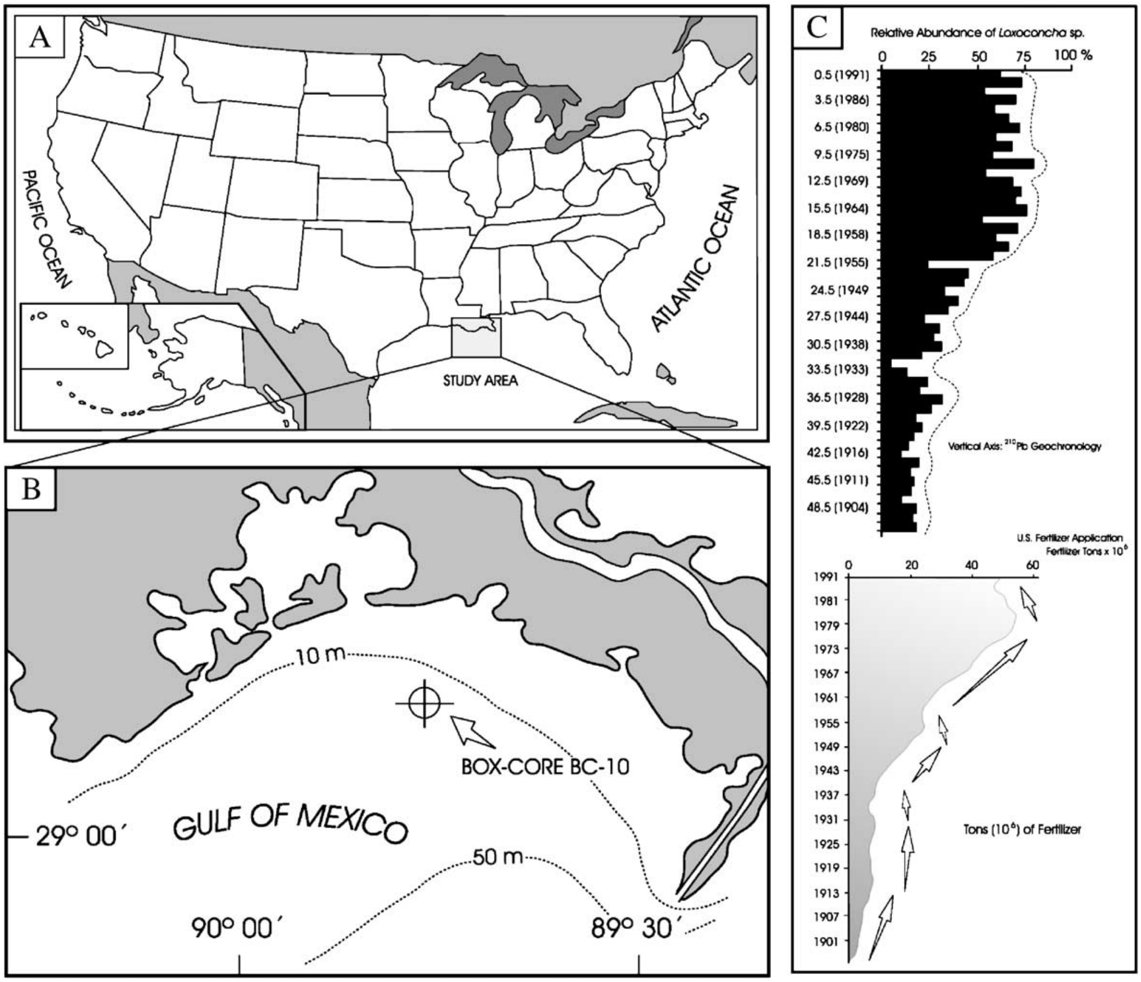

Fig. 9. Comparison between the relative abundance of *Loxoconcha* sp. in box-core BC-10 (Gulf of Mexico) and the amounts of fertilizer application in the United States during the 1900s (modified from Alvarez Zarikian et al., 2000).

during the 1900s (Alvarez Zarikian et al., 2000). A similar trend has been found for *Leptocythere nikraveshae* in the Patuxent estuary and Chesapeake Bay (Cronin and Vann, 2003), with an increasing abundance during the 19th century coinciding with extensive land clearance due to agriculture (Brush, 1984).

Conversely, local inputs of pesticides do not significantly harm the ostracod communities. Edku lagoon (Egypt) receives about 1000 million m^3 of agricultural drainage water annually, but this small area (126 km^2) has unpolluted sediments containing a well-developed ostracod biocoenosis (400–1500 individuals/50 cm^3; Samir, 2000). In addition, the most abundant species (i.e., *C. torosa*) are similar to those observed in other unpolluted lagoons of northern Africa (Carbonel, 1980).

4. Oil spills and ostracodes

The sensitivity of the ostracod assemblages to the oil pollution observed in the laboratory and field experiments has been contrasted in different oil spill situations (Table 3). In these cases, the application of the former methodological procedures may produce some misleading results, because the oil particles are removed from the valves during washing in the laboratory (Mostafawi, 2001). Consequently, an artificial decrease in the number of oil-affected individuals may be produced.

4.1. Tankers

The effects of some tanker accidents on the ostracods are calamitous, with a significant decrease of both densities and diversities within the first weeks after the spill in relation to the control sites. In Narragansett Bay (Rhode Island, USA), scarce living individuals of ostracods coexist with juvenile specimens of amphipods after an oil spill (Widbom and Oviatt, 1994), although it may have been a temporary effect. In the northeastern part of the Strait of Magellan, the ostracod population was affected by a petroleum spill only in the shallower zones, where a recuperation of the initial biocoenosis was found 20 months after the spill (Kaesler et al., 1979).

4.2. Wars

Massive oil spills poured into the Persian Gulf as a consequence of the 1991 Gulf War. On the Iranian coast, these discharges caused a calamitous effect on

Table 3
Effects of oil discharges on the ostracod faunas

Location	Oil source	Ostracod response	Reference
Balthic Sea	Microcosm experiment (oil refinery effluents)	Six months of treatment: decreasing numbers in the high dosage mesocosms. Fifteen months of treatment: increasing numbers in most taxa. Eutrophicating rather than toxic effects on ostracod assemblages	Liljenstroem et al., 1987
Narraganset Bay, Rhode Island, USA	Tanker "World Prodigy"; 922 Tn fuel oil	Lower densities at the most heavily impacted stations	Widbom and Oviatt, 1994
Review of meiofaunal response to oil-induced disturbance		Temporary effects, with an initial strong mortality and a later change in trophic structure	Danovaro, 2000
Louisiana (LA: chronical exposition)–Mississippi (MI: uncontaminated), USA	Microcosm experiment	Abundance negatively impacted to a greater extent in MI than in LA	Carman et al., 2000
Persian Gulf	1991 Gulf War: Kuwaiti oil wells	Very heavy mortality (only 2 of 3114 specimens with soft bodies). Death individuals with completely closed carapaces. Oil particles accumulated mainly in the central part of the carapace	Mostafawi, 2001
Vladivostok, Russia	Harbour area	No living ostracods found in the heaviest polluted area	Schornikov, 2000
Terrebonne Bay Estuary, Gulf of Mexico, USA	Microcosm experiment	Significant reduction in the diesel treatment. Unappreciable effects in the metal treatment	Millward et al., 2004

the ostracod faunas, with rare living individuals (2 of 3114). The most contaminated samples present 3–5% of the complete carapaces with oil residues, which accumulate in the central part of the carapace (Mostafawi, 2001).

4.3. Harbours

No ostracods were found in the main entrance channels of Vladivostok harbour, where the bottom sediments are covered by an oil film that stops the algal growth (Fig. 10; Schornikov, 2000).

4.4. Medium to long-time evolution

These data indicate that a strong mortality was induced immediately (days to few months) on ostracods by the subsequent toxicity generated in the bottom sediments. This oil disturbance has generally only temporary effects after the spill (Kaesler et al., 1979), but new trophic structures were observed with important changes in the ostracod assemblages (Danovaro, 2000).

5. The ostracod carapace geochemistry as environmental tracer

5.1. Methodological risks

These investigations have been focused on the relationships between the geochemical composition of the ostracod valves and the environmental variables (Table 4). The methodological protocol needs to be extremely careful, with the location of the sampling points in the same position on all valves studied. If this procedure is omitted, conclusions may be mistaken owing to the significant anisotropy present in the distribution of one or several elements in specimens belonging to the same species.

Antero-posterior differences are common in the marine species *Leptocythere psammophyla*, whereas variations between inner and outer parts of the shells are less frequent in this species (Bodergat et al., 1993). Nevertheless, *C. torosa*, one of the commonest brackish species, presents its absolute maximum values of Mg in the inner part of the carapace, whereas Ca is more concentrated in reticulation cavities and Mg, Sr,

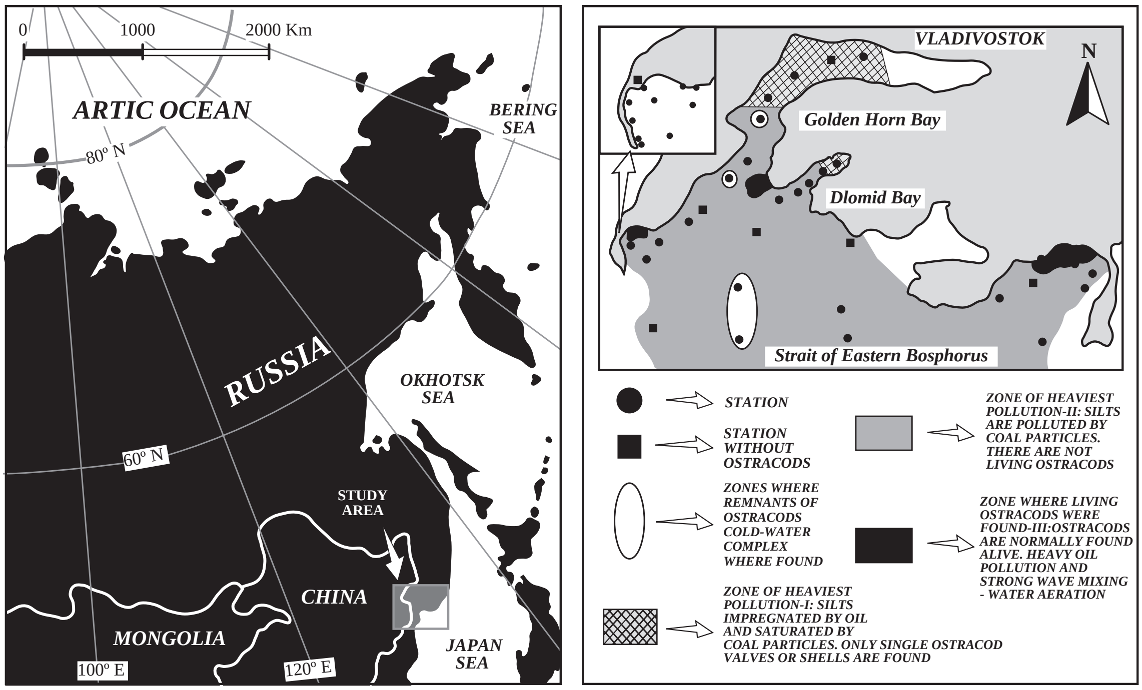

Fig. 10. Distribution of ostracod complexes in the Vladivostok port area, eastern Russia (modified from Schornikov, 2000).

Table 4
Influence of the water composition on the geochemistry of the ostracod valve under different environmental conditions

Location	Ecology	Species	Element	Main conclusions	Reference
Camargue (SE France)–Alicante (SE Spain)	Brackish	*Cyprideis torosa*		Higher contents in closures near a paper-mill	Bodergat, 1983; Bodergat et al., 1991.
Bouches-du-Rhône, Marseille, France	Marine	17	Whole X-ray diffraction diagram	Occurrence of cerium in *Aurila speyeri*, near a sewer of fire-proof industries	Bodergat, 1978a, 1998.
World-wide scale	Freshwater–Brackish–Marine	19	P	Phosphates with uniform distribution along the valve thickness. Variations between different species collected in the same sample	Bodergat, 1978b
SE France–SE Spain	Brackish	*Cyprideis torosa*	Twenty-five elements	Detection of industrial and domestic wastes by the presence of pollutants (Pb, Ni, Sn) in the ostracod valves	Bodergat et al., 1991
	Marine	*Leptocythere psammophyla*		Chemical composition of the shell depends possibly on urban pollution	Reyment, 1996
Baltic Sea–North Sea–English Channel	Marine	*Leptocythere psammophila*	Si–Al–Fe–Ca–Mg–Na–Mn–Ba–Sr–P–S–Cl	Anisotropic fixing of elements in the carapace before or during moulting. Distribution of elements controlled by metabolism and passive trapping	Río et al., 1997
Menorca Island (Spain)–Lee Stocking Island (Bahamas)–Tamiahua Lagoon (Mexico)	Brackish–Marine	*Cyprideis* spp.	Thirty-eight trace elements	Anthropogenically-induced accumulation of Mn in ostracod valves in polluted sites	Palacios-Fest et al., 2003

Na, Fe, P and Si concentrate mostly in ridges (Carbonel and Tölderer-Farmer, 1988).

In addition, a low number of valves (<100) are used in most cases. Consequently, results are based on the analysis of an insufficient number of valves to undertake statistical analyses (Bodergat, 1978a,b).

5.2. The ostracod carapace geochemistry

Few studies have compared the occurrence of trace metals and other carapace components in ostracod valves from recent sites of varying contamination levels (Table 4), with the nature of the contaminant discharges. Carapaces of *Cyprideis* spp. have significant differences in the Mn, Fe and rare-earth element contents between unpolluted and polluted lagoons of America and Europe, whereas Cd and Pb did not have this distinction (Palacios-Fest et al., 2003). In Camargue (France), the chemical composition of *C. torosa* changes in the vicinity of chlorine-rich industrial sewages, with the highest concentrations of chlorides and Fe in relation to unpolluted sites (Bodergat et al., 1991).

In addition, the potential value of an instar as an instantaneous marker of the environmental conditions has been also demonstrated. Near Marseille (France), the carapace of *Aurila speyeri* Brady concentrated Ce due to an eventful discharge of a big sewer during moulting (Fig. 11; Bodergat, 1978a).

6. Conclusions

In the last two decades, the utility of ostracods as environmental markers in brackish and marine areas has been demonstrated in numerous environmental investigations. Recent experiments have showed the high sensitivity of these microcrustaceans to oil con-

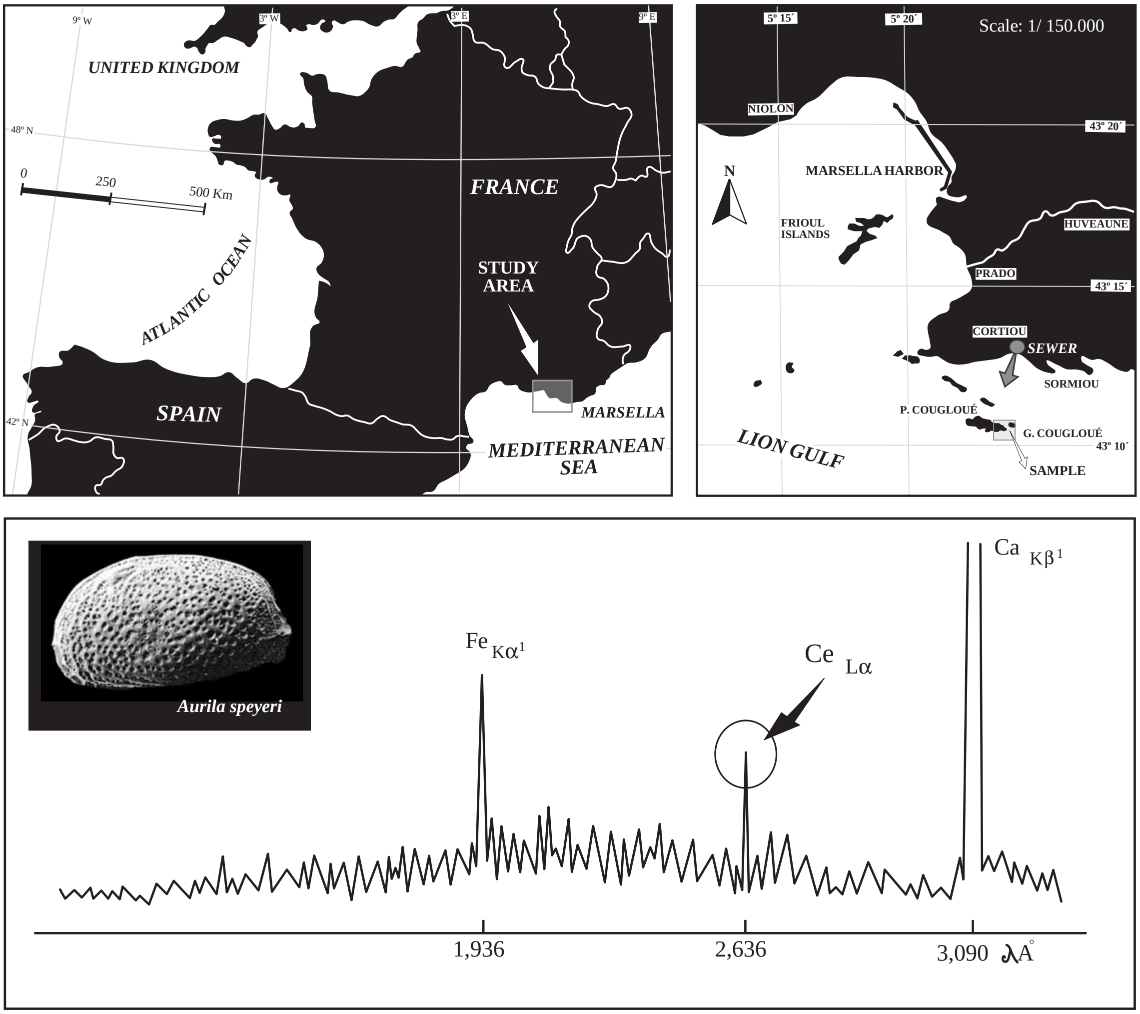

Fig. 11. Location of the sample collected near the Cortiou emissary (southern Marseille, France) and Ce detection in a valve of *Aurila speyeri* (modified from Bodergat, 1978a).

tamination and, to a lesser extent, to heavy metals, with an initial severe damage that diminishes with time than amphipods, microalgae, sprintails or other crustaceans. This sensitivity has been verified in meiofaunal investigations, where ostracods contribute significantly to the distinction between the control samples from the disturbed areas disturbed by heavy metal pollution and fish-farming.

Anthropogenic discharges to the aquatic environment have variable effects on the ostracod assemblages, depending on the nature of the wastes. Heavily polluted sewages of different sources (fertilizers, petroleum byproducts, chemicals, mining) may cause the total disappearance of the crustaceans in the areas adjacent to the effluents. Analysis of box cores allows delimitation of the size of the polluted area or the temporal effects of the pollution. Other residues (urban, agriculture) have a limited effect on the ostracod densities and diversities, with variable eutrophication levels according to the degree of treatment. Oil spills are calamitous for ostracods, with a strong mortality in the contaminated surface sediments. All these impacts are detected in the carapace geochemistry, which may detect eventful discharges during the moulting processes.

In conclusion, ostracods fit very well with the characteristics of animal sentinel systems (Committee on Animals as Monitors of Environmental Hazards of the U.S. National Research Council, 1991) for the following reasons:

1. They have a wide distribution in the aquatic environment.
2. They are easily collected and picked up in samples of surface sediment.
3. Most of the time, population density is sufficient to allow enumeration of species and individuals.
4. Their response to the pollutants is measurable by changes of richness indices (densities, diversities) or their chemical composition.

The ostracod analysis reveals as a robust environmental tool with very low economical cost for the public or private managers responsible of the brackish and marine ecosystem sustainability. In addition, all these features are clearly applicable to the reconstruction of the history of anthropogenic impacts on ostracods based on sediment-core analysis.

Acknowledgements

We thank T. Cronin and an anonymous referee for the critical reading of this report. This paper is a contribution to the COLASU Project (ICA3-CT-2002-10012: Sustainability of Mediterranean Coastal Lagoon Ecosystems under semi-arid climate).

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