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Chernobyl Radionuclides in the Mediterranean Seagrass *Posidonia oceanica*, 1986–1987

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ABSTRACT

Between 26 April and 1 June 1986, the nuclear reactor accident of unit 4 at Chernobyl led to the release of a large quantity of radioactive material, part of which reached the Mediterranean environment. Radionuclides such as ^{103}Ru, ^{106}Ru, ^{110m}Ag, ^{134}Cs, ^{137}Cs, ^{141}Ce *and* ^{144}Ce *were immediately detected in the Mediterranean seagrass* Posidonia oceanica *(L.) Delile. A survey of this species showed a selective distribution amongst its tissues and a preferential contamination of the adult leaves. The rhizomes, which are perennial parts, recorded early contamination by* ^{110m}Ag, *located by sectioning the annual segments (lepidochronology). Variations in the concentrations of several radionuclides found in adult leaves reveal the*

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rapid decay and distribution of contamination in Mediterranean waters in 1986 and 1987, although the eastern part of the French coast had higher concentrations in 1986. Since adult leaves are continuously renewed and because of their rapid accumulation of radionuclides, they may be particularly interesting immediate sentinel accumulators in the event of a nuclear accident as well as in monitoring chronic contamination. It is suggested that a 'Posidonia Watch' could be set up around the Mediterranean Sea.

INTRODUCTION

Posidonia oceanica (L.) Delile meadows constitute a climax biocoenosis of shallow near-shore waters down to 40 m depth, indigenous in the Mediterranean Sea (Molinier & Picard, 1952; Pérès & Picard, 1964; Hartog, 1970). In addition to stabilizing marine sediments and protecting the shoreline (Jeudy de Grissac, 1975), seagrass beds are an important site of primary production (Libes, 1984), acting as a spawning area, nursery and protective area for numerous fish (Harmelin-Vivien, 1982), the leaves and rhizomes offering support for epiphytic organisms which constitute a complex foodweb.

P. oceanica is widely spread over the western and eastern Mediterranean basins with a temporal persistence of leaves which are regularly renewed every 20–56 weeks (Ott, 1980). This species is sensitive to acute levels of pollution, being absent near sewage outfalls (Pérès & Picard, 1975) and can be considered an indicator species, as defined by Gray and Pearson (1982), as its change in abundance in an area can reflect the effects of marine pollution. But, as shown with other species such as *Halodule wrightii* and *P. australis*, the seagrass can also be considered as a sentinel accumulator to assess the temporal and geographic contamination of a site by studying the concentrations of contaminants in the leaf tissues (Pulich, 1980; Ward, 1987). Thus, previous field studies of northwestern Mediterranean seagrass have shown that *P. oceanica* leaves and rhizomes can concentrate various pollutants such as metals, i.e. mercury (Augier *et al.*, 1977; Maserti *et al.*, 1988) and copper, lead and cadmium (Chabert *et al.*, 1983), and organochlorinated compounds, e.g. DDT, lindane and PCB (Chabert *et al.*, 1984), and artificial radionuclides (Calmet *et al.*, 1985; Florou *et al.*, 1985). However, the heterogeneous, spatial and temporal distributions of pollutants in seagrass tissues have recently been linked to plant growth as well as to the heterogeneity of the sea water contaminant levels (Ward, 1987). Therefore, radioactivity concentrations in the leaves, the scales (which are the sheath of dead leaves) and the rhizome sections show a heterogeneous distribution relative both to the levels of radionuclides in the sea water at a precise time and to the different concentration factors specific to each tissue (Calmet *et al.*, 1988*a*). Moreover, metal accumulation in seagrass *H. wrightii* (Pulich, 1980) and *P. australis* (Ward, 1987) appeared to depend more on leaf age than on variations in metal concentrations in industrial discharges.

Between 26 April and 1 June 1986, the Chernobyl unit 4 reactor explosion and fire led to widespread, substantial emissions of a large array of radionuclides (INSAG, 1986). During the days following the explosion, large areas of the Mediterranean Sea were subject to radioactive fallout (CEA, 1986; Smith, 1988) which was identified in aerosols collected in the eastern part of the French coast (Ballestra *et al.*, 1987). Subsequently, the artificial radioactivity of the sea water in the northwestern basin increased markedly (Whitehead *et al.*, 1988) due to soluble radionuclides such as ^{134}Cs and ^{137}Cs (Calmet *et al.*, 1988*c*).

The aim of the present study was to examine the temporal and spatial changes in radioactivity concentrations in leaf and rhizome tissues of *P. oceanica* before and after the Chernobyl fallout to determine the suitability of this species as a sentinel organism or a sentinel accumulator to monitor accidental contamination. The study was carried out along the French Mediterranean coast which was contaminated both by direct Chernobyl fallout on the sea surface at the study sites and by indirect input of contaminated sea water from the Ligurian east-westward current flowing from the northwestern Italian coast.

MATERIALS AND METHODS

Study area

In 1986 and 1987, *P. oceanica* samples were collected at various sites along the shoreline of the northwestern French Mediterranean basin including Corsica (Fig. 1). Some sites are subject to major river inputs, e.g. the Rhône at the Gulf of Fos, and others to less significant inputs, e.g. the Var at Antibes. Others are largely unaffected by land-based inputs, such as Galeria, on the Corsican coast, or Villefranche, a continental site. The Toulon site, at which monitoring as a function of time was particularly detailed, is located in a large sheltered embayment into which flow small coastal streams.

The *P. oceanica* meadows of the study sites belong either to type II of Giraud (1977) such as the Galeria bay site, i.e. shoot density ranges

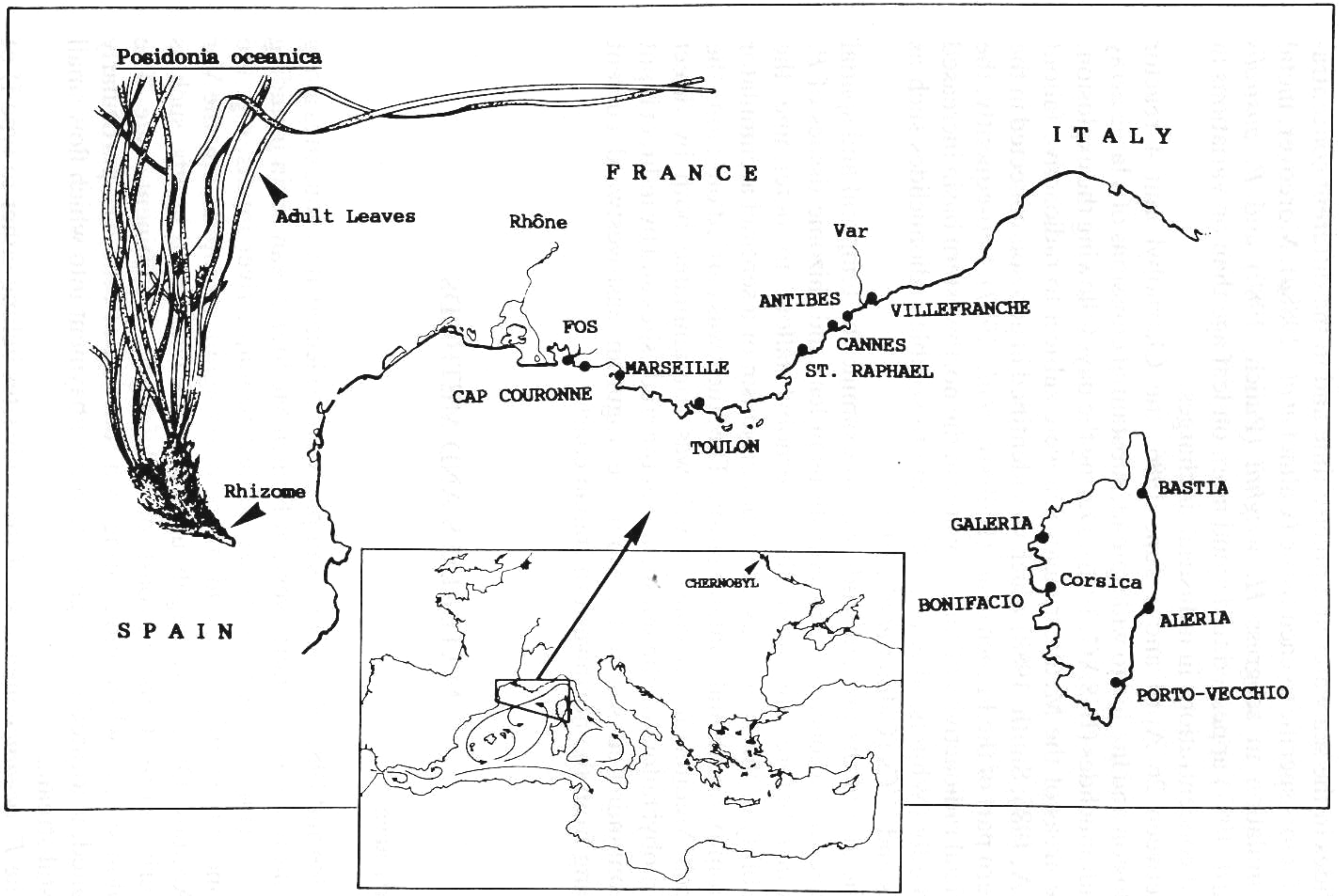

Fig. 1. Map of the North West Mediterranean basin with the sampling site locations. The inset shows the marine currents in the basin and the Chernobyl site.

between 400 and 700 shoots m^{-2} with orthotropous rhizomes up to 75 cm long, average 40 cm, corresponding to an age of 25 years, or to type III with a low density between 300 and 400 shoots m^{-2} with orthotropous rhizomes, 10 cm long on average when 15 years old.

Samples of *P. oceanica* weighing some 2 kg were randomly collected by diving in dense and homogeneous seagrass beds growing at depths of between 10 and 15 m.

Radioactivity measurements

In the laboratory, shoots composed of bundles of 5–10 leaves (Panayotidis & Giraud, 1981) were cleaned of epibiota. Two types of leaves were distinguished: adult leaves with a sheath and intermediate, younger leaves without a sheath. The Galeria and Toulon rhizome samples were cut into annual sections as described elsewhere (Calmet *et al.*, 1988*a*) following the observations by Crouzet *et al.* (1983) and the method based on the presence of scale cycles along the rhizome used by Pergent *et al.* (1983) termed lepidochronology (Boudouresque *et al.*, 1983). Thus, the 1986 annual section and different previous annual sections were isolated.

All samples of *P. oceanica* adult leaves, intermediate leaves and rhizome annual sections were dried at 60°C for 72 h and reduced to a homogeneous powder in a ball mill. Artificial and natural gamma-emitting radionuclides in the powder were measured using a 300 ml standardized container and direct spectrometry. A high resolution Ge detector, of 44% efficiency, calibrated with standard sources of known activity and with an energy range from 2 keV to 1·33 MeV, was used, the counting time being approximately 1200 min. The data are given as Bq kg^{-1} dry material at sampling date.

RESULTS AND DISCUSSION

Before the Chernobyl accident, the only artificial gamma-emitting radionuclide found in *P. oceanica* leaves and rhizomes was ^{137}Cs, at below 1 Bq kg^{-1} dry weight (Calmet *et al.*, 1985), this being of weapons test fallout origin, which reached a maximum in 1963 (UNSCEAR, 1982). From May 1986 onwards, some Chernobyl radionuclides were found in the various parts of *P. oceanica* collected along the northwestern basin coastline.

Plant radioactivity distribution

The data in Table 1 show the radionuclide distribution in the parts of *P. oceanica* during the months following the Chernobyl accident. ^{103}Ru,

TABLE 1

The Distribution of Artificial Radionuclides in *Posidonia oceanica* Leaves (Intermediate and Adult) and Rhizomes, as Found in Samples Collected at 3 Stations of the French Mediterranean Coast

Site/sample	*Radionuclide*						
	^{103}Ru ±1σ	^{106}Ru ±1σ	^{110m}Ag ±1σ	^{134}Cs ±1σ	^{137}Cs ±1σ	^{141}Ce ±1σ	^{144}Ce ±1σ
Toulon (13 June 1986)							
Adult leaves	148·5 ± 14·0	136·0 ± 20·0	20·4 ± 2·0	1·6 ± 0·7	5·1 ± 0·7	BDL	73·2 ± 11·0
Intermediate leaves	74·3 ± 7·0	80·0 ± 11·0	18·9 ± 2·0	1·1 ± 0·5	2·1 ± 0·5	10·4 ± 1·5	38·4 ± 5·7
Rhizomes:							
1986 section	BDL	BDL	72·2 ± 10·8	BDL	BDL	BDL	BDL
1985 section	BDL	BDL	46·6 ± 7·0	BDL	BDL	BDL	BDL
1984–1977 section	BDL	BDL	13·4 ± 2·0	BDL	BDL	BDL	BDL
Galeria (Corsica, 20 July 1986)							
Adult leaves	73·6 ± 7·4	156·6 ± 23·5	27·4 ± 4·1	BDL	3·5 ± 1·6	BDL	BDL
Intermediate leaves	45·4 ± 6·8	BDL	52·5 ± 5·3	1·3 ± 0·7	BDL	BDL	BDL
Rhizomes:							
1986 section	BDL	BDL	23·2 ± 3·5	BDL	BDL	BDL	BDL
1985 section	BDL	BDL	11·0 ± 1·6	BDL	BDL	BDL	BDL
1984 section	BDL	BDL	32·4 ± 4·9	BDL	BDL	BDL	BDL
Gulf of Fos (28 July 1986)							
Adult leaves	34·3 ± 3·5	55·4 ± 15·4	16·5 ± 2·5	BDL	2·8 ± 1·3	4·6 ± 2·0	22·7 ± 10·2
Intermediate leaves	20·8 ± 3·1	BDL	20·9 ± 3·1	BDL	1·5 ± 0·7	BDL	BDL

Data are expressed in Bq kg^{-1} dry weight at the sampling date.
BDL, Below detection limit.

^{106}Ru, ^{110m}Ag, ^{134}Cs, ^{137}Cs, ^{141}Ce and ^{144}Ce were detected in *P. oceanica* adult leaves, whereas only ^{110m}Ag was detected in rhizome sections. At Toulon, Galeria and Cape Couronne, adult leaves were more contaminated than younger leaves which in turn were more contaminated than the apical rhizome sections, ^{110m}Ag excepted. At the Toulon site, the apical section and the subsequent growth sections of the rhizome were contaminated only by ^{110m}Ag, with concentrations decreasing with the rhizome section age, whereas, at the Galeria site, the ^{110m}Ag concentrations did not decrease with rhizome section age.

Marine phanerogam capacity to absorb solutes via their leaves and roots (Kuo, 1978), as shown for *P. oceanica* with phosphorus (Fresi & Saggiomo, 1981), and the fact that the photosynthesis rate for *P. oceanica* usually reaches a peak in May (Caye, 1989) are two aspects that have certainly encouraged rapid adult leaf contamination by radionuclides in solution following fallout deposition from the Chernobyl accident. Rhizomes do not show a comparable capacity to accumulate solutes, although roots which are growing from the rhizomes do. The ^{110m}Ag rhizome contamination could be explained on the grounds that, as ^{110m}Ag is usually found in particulate form which sediments rapidly, it could be adsorbed on to the rhizome surface from the sediment.

Because of their capacity to accumulate rapidly a larger spectrum of radionuclides and because of their continuous renewal throughout the year (Crouzet *et al.*, 1983), *P. oceanica* adult leaves appear to be an interesting immediate sentinel accumulator tissue of chronic or accidental introduction of radionuclides into the marine environment. *P. oceanica* scales, which are the persistent part of the leaf, record past radionuclide contamination, as has already been demonstrated (Calmet *et al.*, 1988*a*). Since there is a large concentration difference between intermediate and adult leaves, the leaf samples must be selected so as to prevent radionuclide dilution in a heterogeneous sample.

Temporal distribution

At the Villefranche and Toulon sites, where we obtained precise time series for 1986 and 1987 respectively, adult leaf samples showed an increase in ^{103}Ru, ^{106}Ru, ^{110m}Ag, ^{134}Cs, ^{137}Cs, ^{141}Ce and ^{144}Ce in the months following the Chernobyl accident (Table 2). This increase of radioactivity in adult leaves observed in May in Villefranche and June in Toulon was due to the temporary increase of radioactivity in the upper layers of the coastal water column (Calmet *et al.*, 1988*c*; Whitehead *et al.*, 1988), where *P. oceanica* grows, following the vertical mixing of the sea water surface layer contaminated by direct Chernobyl fallout. The temporal evolution of radioactivity levels in adult *P. oceanica* leaves is subsequently described for Villefranche in 1986 and Toulon in 1987.

In this context, ^{141}Ce and ^{144}Ce concentrations in adult leaves fell rapidly in 1986 at the Villefranche site, as expected due to their affinity for the particulate phase. This fast decrease of the cerium isotopes is probably linked to its chemical behaviour in sea water in which cerium is found mainly in particulate form or as CeO_2 sorbed on to suspended material (Sugihara & Bowen, 1962; Carpenter & Grant, 1967; Hirano *et al.*, 1973). Thus, cerium is rapidly removed from the water column by particulate sedimentation, as shown by Buesseler *et al.* (1987) in the Black Sea. The difference in the decrease of concentrations between the two isotopes, from 130 to 3 Bq kg^{-1} dry weight in six months for ^{144}Ce, while ^{141}Ce disappears after four months from concentrations of 110 Bq kg^{-1} dry weight, can also be partly explained as these elements are short-lived, with half-lives ($t_{1/2}$) of 39·6 days and 284·8 days for ^{141}Ce and ^{144}Ce respectively.

Similarly, the decline in ^{106}Ru ($t_{1/2} = 369$ days) from 199 to 12 Bq kg^{-1} dry weight in less than six months could be explained by the formation of polymeric chemical forms. These could react with suspended and organic material, as has been described for coastal areas receiving low-level radioactive liquid waste releases from reprocessing plants (Calmet & Guegueniat, 1985). Although ^{103}Ru was released in larger amounts than ^{106}Ru, in the ratio 2·7 (CEA, 1986), the difference in decrease rates of the two isotopes, from 270 to 12 Bq kg^{-1} dry weight for ^{106}Ru and from 626 to 3 Bq kg^{-1} dry weight ^{103}Ru in less than six months, can again be partly explained by the difference in their half-lives, 32·5 days and 369 days respectively for ^{103}Ru and ^{106}Ru.

^{137}Cs ($t_{1/2} = 29{\cdot}4$ years) is a longer-lived radionuclide which was found in the Chernobyl fallout with the same aerosol particle size as in the fallout from nuclear weapon tests (Jost *et al.*, 1986) and is usually present in sea water in hydrated cationic form (Freiling & Ballon, 1962). Concentrations dropped suddenly from 32 to 4·4 Bq kg^{-1} dry weight in a month and stayed close to this value until the end of the year. As for ^{134}Cs ($t_{1/2} = 2{\cdot}1$ years) activity, it declined from 12 to 2·2 Bq kg^{-1} dry weight and then remained constant. Since it was certainly present in lower amounts in the fallout (CEA, 1986), the ^{134}Cs concentrations are lower than those for ^{137}Cs. Caesium is less particle-reactive than cerium or ruthenium (Duursma & Gross, 1971) but there may be a reversible exchange with the solid phase leading to partial sedimentation and an important degree of mixing with uncontaminated deeper water (Whitehead *et al.*, 1988).

The decrease in ^{110m}Ag ($t_{1/2} = 253$ days) from 34 to 21 Bq kg^{-1} dry weight in six months is small relative to those for the other radionuclides. In sea water, ^{110m}Ag is chiefly found as a soluble monovalent cation which can interact with ligands to form an anionic chlorinated complex which does not precipitate (Fukai & Huynh-Ngoc, 1966). It is usually found to be associated (up to 80%) with seston in coastal water (Carpenter & Grant, 1967). This element was certainly generated via ^{110}Cd(n,p) ^{110}Ag reactions, as cadmium is used as a neutron absorber in nuclear reactors (Jones *et al.*, 1986). ^{110m}Ag, which was only rarely reported in environmental samples measured in Western European countries after the Chernobyl accident, was detected here in the adult leaves and rhizome samples. Representing 2% of the total initial radioactivity from Chernobyl fallout in *P. oceanica*, ^{110m}Ag is the major contributor to Chernobyl contamination five months later, making up more than 48% of the anthropogenic radionuclide activity found in the seagrass leaves.

During 1987, as can be seen in the radionuclide time-series from Toulon, the decrease of radionuclide concentration in adult leaves continued (Table 2). By October 1987, only caesium isotopes were detectable. The persistence of ^{134}Cs and especially ^{137}Cs, both in a soluble form, shows that the chemical form is a major factor in radionuclide bio-availability.

The subsequent temporal decrease in radioactivity can be ascribed to a biological effect as dying leaves drop off and are replaced by intermediate leaf growth in adult leaves in a less contaminated environment. The progressive decrease of artificial radioactivity in sea water can be explained by water replacement from less contaminated areas in the southern part of the western basin, scavenging from surface to deeper layers of the water column and radioactive decay of the short-lived radionuclides.

Spatial distribution

Sampling cruises were organized in November 1986 to cover the eastern part of the French continental coast and in July 1987 to cover the Corsican coast (Fig. 2). In November 1986 (Table 2), with the exception of cerium isotopes in Toulon, all the radionuclides initially measured between May and June 1986 were still found in *P. oceanica* adult leaves from Villefranche to Toulon. At the westernmost site, Cape Couronne, only ^{137}Cs and ^{110m}Ag were detected and their concentrations found to be lower than those at sites to the east. This spatial distribution confirms the fallout pathway through the eastern part of the northwestern Mediterranean basin (CEA, 1986) and the radioactivity gradient observed in *Mytilus* sp. along the French Mediterranean coast (Calmet *et al.*, 1988*b*).

In July 1987 (Fig. 2), apart from ^{137}Cs and ^{110m}Ag, most of the radionuclides originating in the Chernobyl fallout had disappeared from

TABLE 2

Artificial Radionuclide Contents in *Posidonia oceanica* Adult Leaf Samples during 1986–1987 at 6 Stations along the Eastern Section of the French Mediterranean Coast

	Radionuclide						
Site/date	^{103}*Ru* ±*1σ*	^{106}*Ru* ±*1σ*	^{110m}*Ag* ±*1σ*	^{134}*Cs* ±*1σ*	^{137}*Cs* ±*1σ*	^{141}*Ce* ±*1σ*	^{144}*Ce* ±*1σ*
Villefranche							
21 April 1986	BDL	BDL	BDL	BDL	BDL	BDL	BDL
22 May 1986	626·0 ± 30·0	199·0 ± 15·0	34·0 ± 4·0	12·0 ± 2·0	32·0 ± 8·0	110·0 ± 11·0	130·0 ± 15·0
1 June 1986	600·0 ± 30·0	270·0 ± 20·0	57·0 ± 7·0	7·0 ± 1·0	16·0 ± 4·0	100·0 ± 10·0	130·0 ± 15·0
26 June 1986	113·0 ± 10·0	124·0 ± 12·0	22·0 ± 2·0	2·2 ± 0·5	4·4 ± 2·0	7·4 ± 1·0	28·0 ± 3·0
8 Sept 1986	50·0 ± 5·0	102·0 ± 10·0	37·0 ± 4·0	3·6 ± 0·5	8·0 ± 3·0	BDL	8·0 ± 3·0
13 Oct 1986	37·0 ± 3·0	140·0 ± 20·0	24·0 ± 3·0	2·6 ± 0·7	4·0 ± 1·0	BDL	8·0 ± 3·0
17 Nov 1986	3·0 ± 0·5	12·0 ± 1·0	21·0 ± 2·0	1·0 ± 0·5	3·0 ± 1·0	BDL	3·0 ± 1·0
Antibes							
20 Nov 1986	3·9 ± 0·8	24·0 ± 15·0	22·0 ± 3·0	1·9 ± 1·0	3·0 ± 1·0	BDL	BDL
9 July 1987	BDL	BDL	BDL	BDL	1·9 ± 1·0	BDL	BDL
Saint Raphael							
8 Nov 1986	BDL	43·9 ± 20·0	32·8 ± 5·0	BDL	6·8 ± 1·0	BDL	BDL
10 July 1987	BDL	BDL	2·8 ± 1·5	BDL	1·6 ± 0·5	BDL	BDL

Toulon							
13 June 1986	148·5 ± 14·0	136·0 ± 20·0	20·4 ± 2·0	1·6 ± 0·7	5·1 ± 0·7	BDL	73·2 ± 11·0
20 Sept 1986	65·5 ± 7·0	50·0 ± 2·0	30·0 ± 4·0	2·0 ± 1·0	5·0 ± 1·0	BDL	BDL
28 Nov 1986	7·0 ± 0·5	30·0 ± 3·0	54·0 ± 8·0	2·0 ± 1·0	5·0 ± 1·0	BDL	BDL
26 Feb 1987	BDL	16·0 ± 2·0	16·0 ± 3·0	1·0 ± 1·0	3·0 ± 1·0	BDL	BDL
14 May 1987	BDL	9·0 ± 1·0	5·0 ± 2·0	1·6 ± 0·8	6·0 ± 1·0	BDL	BDL
16 June 1987	BDL	7·0 ± 1·0	4·0 ± 1·0	1·5 ± 0·9	6·0 ± 1·0	BDL	BDL
16 July 1987	BDL	BDL	3·0 ± 1·0	2·6 ± 0·9	8·0 ± 2·0	BDL	BDL
28 Aug 1987	BDL	BDL	3·0 ± 1·0	2·0 ± 1·0	4·0 ± 1·0	BDL	BDL
30 Sept 1987	BDL	BDL	BDL	BDL	4·0 ± 1·0	BDL	BDL
4 Oct 1987	BDL	BDL	BDL	1·0 ± 0·9	3·0 ± 1·0	BDL	BDL
Cape Couronne							
23 Mar 1986	BDL	BDL	BDL	BDL	1·0 ± 0·5	BDL	BDL
28 July 1986	34·3 ± 3·5	55·4 ± 15·4	165·0 ± 2·5	BDL	2·8 ± 1·3	4·6 ± 2·0	22·7 ± 10·2
3 Nov 1986	BDL	BDL	15·6 ± 6·0	BDL	2·0 ± 0·8	BDL	BDL
Galeria (Corsica)							
20 July 1986	73·6 ± 7·4	156·6 ± 23·5	27·4 ± 4·1	BDL	3·5 ± 1·6	BDL	BDL
25 Sept 1986	35·0 ± 7·0	90·0 ± 20·0	33·0 ± 7·0	BDL	BDL	BDL	BDL
1 July 1987	BDL	BDL	4·4 ± 2·0	BDL	1·5 ± 0·7	BDL	BDL

Data are expressed in Bq kg^{-1} dry weight at the sampling date.
BDL, Below detection limit.

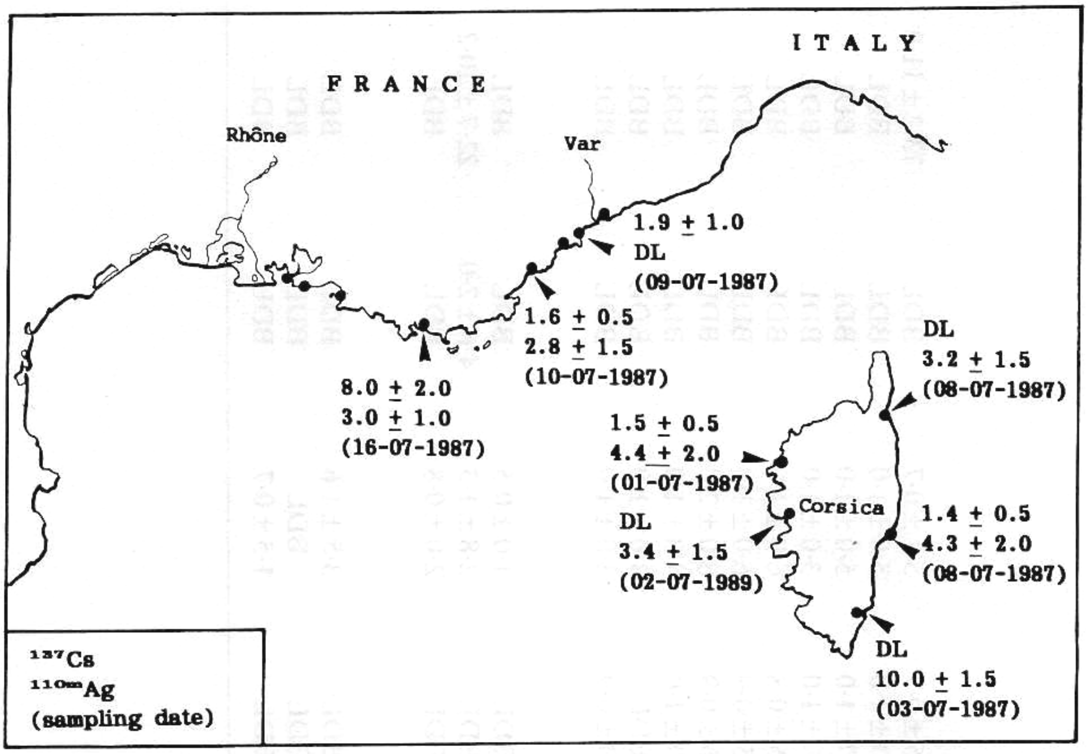

Fig. 2. The spatial distribution of ^{137}Cs (top line) and ^{110m}Ag (second line) in adult leaves of *P. oceanica* sampled in July 1987 (third line) along the French continental and Corsican coasts. Data are expressed in Bq kg^{-1} dry weight at the sampling date; DL, below detection limit.

the adult leaves of *P. oceanica* sampled along the eastern French continental coast and off Corsica. ^{137}Cs activities close to the detection limit oscillate around 1·5 Bq kg^{-1} dry weight, with the exception of the bay of Toulon where the concentration is 8 Bq kg^{-1} dry weight. The latter anomaly reflects the fact that water renewal is slow because the bay is closed off from the open sea by a dyke. ^{110m}Ag concentrations are higher on average, of the order of 3 Bq kg^{-1} dry weight, with a peak of 10 Bq kg^{-1} dry weight in the Corsican bay of Porto-Vecchio. As ^{110m}Ag sediments rapidly after its introduction into the marine environment, thus preventing its dilution/dispersion, it can be considered to be a good indicator of fallout deposition during the first year after the accident.

Coastal configuration seems to have an impact on the degree of contamination of *P. oceanica*. Thus, slow renewal of water in the bay of Toulon appears to prevent the speedy dilution of a soluble radionuclide such as caesium, concentrations diminishing slowly with time. Particulate elements on the other hand, such as silver, are expected to sediment and to be flushed quickly out of the water column. However, the bay of Porto-Vecchio, which is an area of significant sedimentation, is widely exposed to the open sea, providing for dilution of soluble radionuclides such as caesium. Major resuspension occurs there and this should enable remobilization of ^{110m}Ag and subsequent contact with *P. oceanica* leaves.

None of the sampling sites was under the direct influence of the Rhône and Var rivers in estuarine areas where *P. oceanica* has difficulty in growing and therefore the impact of runoff radionuclides cannot be assessed.

CONCLUSIONS

The radioactive fallout from the reactor explosion and fire at Chernobyl contaminated Mediterranean surface sea waters. Subsequently, coastal phanerogams such as *Posidonia oceanica* growing down to 30 m deep were rapidly contaminated. Starting in May 1986, the different parts of *P. oceanica* exhibited an increase in ^{137}Cs activity and ^{103}Ru, ^{106}Ru, ^{110m}Ag, ^{134}Cs and ^{141}Ce and ^{144}Ce became detectable. During 1986, radioactivity levels in adult *P. oceanica* leaves exhibited a rapid decrease, reflecting the decreasing radionuclide content of sea water through mixing between surface and deeper layers plus sinking of radionuclides associated with particles. The decrease in radionuclide concentrations in the adult leaves of *P. oceanica* was used to rank the apparent removal times from sea water, as follows:

$$^{141}\mathrm{Ce} < {}^{144}\mathrm{Ce} < {}^{103}\mathrm{Ru} < {}^{106}\mathrm{Ru} < {}^{110m}\mathrm{Ag} < {}^{134}\mathrm{Cs} < {}^{137}\mathrm{Cs}$$

This series is in full agreement with the observations of Buesseler *et al.* (1987) for Black Sea waters. The major impact of the Chernobyl fallout on the northwest Mediterranean coast was restricted in time to the first year after the accident.

The distribution of artificial radionuclides within plants appeared to be heterogeneous since adult leaves, having remained in contact with soluble radionuclides over longer periods of time, gave higher concentrations of soluble radionuclides than younger intermediate leaves. In contrast, rhizomes, which grow in contact with sediments, were essentially contaminated by cerium which is mainly associated with particles in marine waters. Thus, adult leaves can be used as sentinel accumulators for soluble radionuclide concentrations in sea water and their temporal evolution is due to continuous leaf removal (20–56 weeks). On the other hand, rhizomes and the leaf scales, which are perennial structures that can be cut into yearly sections, can record radionuclide contamination over longer periods, up to 10 years in duration, particularly of long-lived radionuclides such as ^{137}Cs.

P. oceanica can thus be considered to be a valuable bio-indicator of radionuclides, heavy metals and organochlorinated compounds which contaminate the Mediterranean Sea. Since this perennial seagrass is widely spread through the Mediterranean Sea, *P. oceanica* could be integrated into the national monitoring programmes of the Mediterranean coastal states, as demonstrated by past studies in Greece (Florou *et al.*, 1985), France (Calmet *et al.*, 1985) and Spain (Vidal-Quadras *et al.*, 1988). If such a 'Posidonia Watch' was set up, a sampling protocol would have to be clearly devised since the heterogeneous radionuclide distribution within *P. oceanica* necessitates uniform samples of either adult leaves, intermediate leaves or rhizome segments corresponding to a definite year in order to ensure comparability of temporal or spatial data.

P. oceanica beds enable the survival of many species, especially epibiota living on the leaves, which, in addition to their own ability to accumulate radionuclides from sea water, can accumulate radionuclides from *P. oceanica* tissues. In this way, *P. oceanica* can contribute to radionuclide cycling in the coastal marine foodweb, part of which is connected with the human diet. However, the relationships between the concentrations of radionuclides in *P. oceanica* tissue and those in organisms colonizing the seagrass bed have yet to be addressed.

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