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HEAVY METALS AND POLYCICLIC AROMATIC HYDROCARBONS NEAR AN OFF-SHORE GAS-PLATFORM (ADRIATIC SEA): A 3-YEAR MONITORING STUDY

Abstract - A marine area surrounding the off-shore gas-platform Calipso located about 35 km off Ancona in the northern Adriatic Sea was investigated over a 3-year period (2002-2005) with the aim of monitoring the potential effects of the platform on the surrounding sediments 1, 5, 11, 18, 24, 30, 36 months after the end of the drilling operations. Sediments were collected at 17 stations located along two ideal transects intersecting at the platform. Three further stations were chosen as controls 1 km apart, upstream, in an area not influenced by the structure. The sediments were analysed for their particle size and Al, Cd, Cr, Ba, Cu, Hg, Ni, Pb, Zn, polycyclic aromatic hydrocarbons and organic matter content. Some anomalies were detected along the transects during the first sampling survey (2002), that was at the end of the installation phase of the structure. During the following surveys recovery clues were observed as a general decreasing trend of most of contaminants. Longer recovery time was observed for barium and zinc that showed significant anomalies till the end of the monitoring program.

Key words - Monitoring, heavy metals, polycyclic aromatic hydrocarbons, sediments, gas-platform, Adriatic Sea.

Riassunto - *Metalli pesanti e idrocarburi policiclici aromatici in prossimità di una piattaforma gas-metano (Mar Adriatico): 3 anni di monitoraggio*. Nel presente lavoro vengono riportati i risultati di un'indagine di tre anni (2002-2005) condotta a 35 km al largo di Ancona al fine di monitorare i potenziali effetti della piattaforma Calipso sui sedimenti circostanti. Il campionamento è stato condotto 1, 5, 11, 18, 24, 30, 36 mesi dopo la fine delle operazioni di perforazione. I sedimenti sono stati raccolti tramite box-corer in 17 stazioni distribuite lungo due transetti intersecantesi in corrispondenza della piattaforma. Tre stazioni situate 1 km sopracorrente rispetto alla struttura, sono state scelte come controlli. Sui sedimenti è stata effettuata l'analisi granulometrica e sono state determinate le concentrazioni di sostanza organica, Al, Cd, Cr, Ba, Cu, Hg, Ni, Pb, Zn ed IPA (idrocarburi policiclici aromatici). Alcune anomalie sono state evidenziate lungo i transetti durante il primo campionamento (2002) cioè al termine della fase di installazione. Durante le campagne successive sono stati evidenziati segni di miglioramento in concomitanza ad una riduzione della maggior parte dei metalli pesanti. Tempi più lunghi di recupero sono stati rilevati per zinco e bario.

Parole chiave - Monitoraggio, metalli pesanti, idrocarburi policiclici aromatici, sedimenti, piattaforme gas-metano, Mare Adriatico.

Introduction

Since the 1960s, more than 90 off-shore gas platforms have been constructed in the central and northern Adriatic Sea (Bombace *et al*., 1999; Fabi *et al*., 2005). Hence this area has the highest concentration of platforms of the Mediterranean basin. These platforms are situated under a wide range of environmental conditions from shallow to deep waters with different types of sediments (from mud to sand) under or not the influence of the Po river that is the main source of fresh water into the Northern Adriatic Sea (Cattaneo *et al*., 2003).

Inevitably, all kinds of drilling are associated with drilling wastes, including drilling muds and cuttings as reported in the large amount of studies carried out in the North Sea, the Gulf of Mexico and Australia. Even water-based gas-platforms, as those of the Adriatic Sea, although less toxic than their oil-based counterparts (Olsgard & Gray, 1995), produce large quantities of water that may contain elevated concentrations of metals, hydrocarbons and other chemical agents that can cause potential impacts to the surrounding seabed and in turn to the biotic compartment.

In the Adriatic Sea the first studies, aiming to investigate the effects of drilling and exploitation of a methane gas deposits date back to mid-1980s (Frascari *et al*., 1992; Modica *et al*., 1998). In the following years the researches that have been performed to evaluate the drilling impact are mostly limited to technical reports that constitute the so called «grey literature» which is not readily available through normal book selling channels, and therefore difficult to identify and trace (Auger, 1998).

In the few published papers particular attention was paid to the impact of platforms on benthic communities (Frascari *et al*., 1991, 1992; Fabi *et al*., 2007), fish assemblages (Fabi *et al*., 2002, 2004), heavy metal and organic pollutant accumulation both in sediments (Guerzoni *et al*., 1984; Frascari *et al*., 2000; Ferrari *et al*., 2002) and in filter feeding organisms (Mauri *et al*., 1998; Ferrari *et al*., 2003, 2004; Mauri *et al*., 2004), but they are still scarce considering the high drilling activity in the Adriatic Sea.

In addition for the large variety of environments where the platforms are located, a general impact model can not be sufficient to describe the overall situation.

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In fact, it is widely accepted (Breuer *et al.*, 2004) that each case study represents an unique combination of sediment characteristics, contaminants and benthic community and each is differently affected by the local hydrodynamic regime.
Even in the North Sea and in the Gulf of Mexico, where a large amount of studies have been carried out, an unambiguous model on the impact of drilling activities on the surrounding sediments can not be formulated (Olsgard & Gray, 1995).
In the Adriatic Sea a first attempt, although not exhaustive to describe the impact of drilling, was carried out by Fabi *et al*. (2005), who identified two different impacts taking as examples two 4-leg platforms located at different depth and distance from the mainland: the platform Regina, placed in shallow waters (21-22 m depth and 16 km from the coast) on sandy-mud sediments and the Barbara NW platform, situated (70 m depth and about 60 km from the coast) on a muddy sand seabed.
The aim of the present study was to investigate a third scenario, represented by the 4-leg gas-platform Calipso, located at the same depth of Barbara NW but at an intermediate distance from the coast in respect to Barbara NW and Regina.
In this paper, part of an environmental impact monitoring, special attention has been paid to identify changes in sediment contamination because sediments incorporate pollutants over a long period and are thus appropriate for monitoring the status of an area.
Heavy metals and polycyclic aromatic hydrocarbons were investigated from 2002 to 2005 to evaluate their impact on the sediments and their temporal variations over a three year period starting from the end of the installation of the structure. Organic matter and grain size were also determined.

Materials and methods

Study area and sampling strategy

The platform Calipso (hereafter PC) is located on a muddy seabed approximately 35 km off Ancona (Adriatic Sea) in 75 m of water (Fig. 1). The main current at the sea bottom flows from NE towards SE, following the basin topography and has a speed of 5-10 cm s^{-1} sporadically reaching 20 cm s^{-1}.
The structure was installed in May 2002 and the drilling operations started in the following month and finished in October 2002. Production began immediately after. The first sampling was performed about 1 month after the drilling activities ceased (November 2002). The following 6 field cruises were carried out from 2003 to 2005, *i.e.* 5, 11, 18, 24, 30, 36 months after the end of the drilling operations.
The sampling design was planned according to the «gradient design» approach that is particularly useful when a stressor or disturbance attenuates with the distance from the point source of the impact (Ellis & Schneider, 1997).

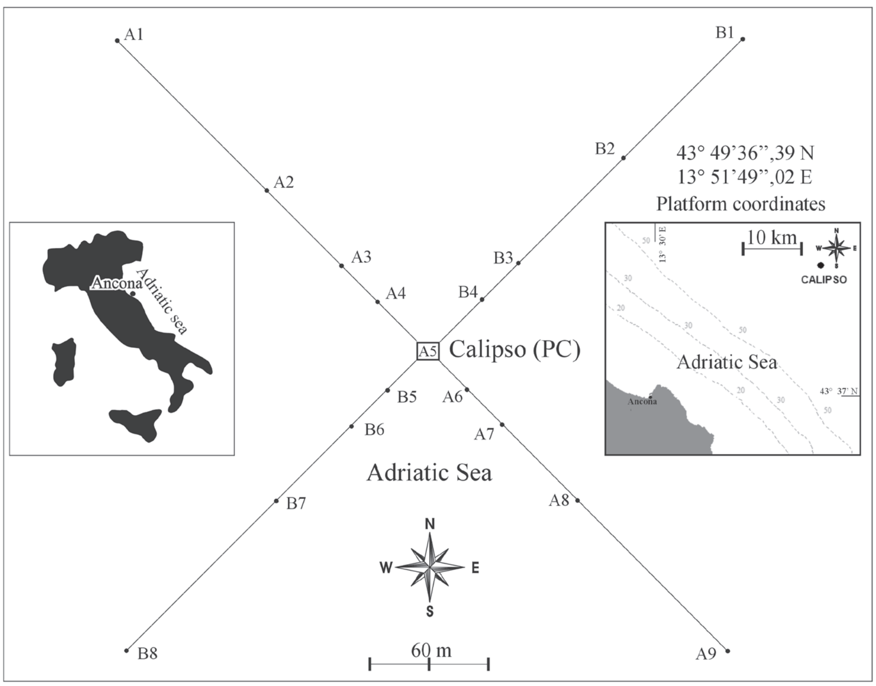

Fig. 1 - Calipso platform (PC) and sampling stations.

This design is basically a cross similarly to that described by Olsgard & Gray (1995) following directives prepared by the Norwegian State Pollution Control Authority.

Hence the sampling sites were arranged along two ideal transects intersecting at the structure. One transect was oriented NE-SE (in parallel with predicted main current movements), a second axis was chosen orthogonal to the first. A total of 17 stations (hereafter Treatments, T) were located at geometrically increasing distances from the platform (PC, 30, 60, 120, 250 m) (Fig. 1). Three further stations were chosen as controls (C) 1 km apart, upstream, in an area not influenced by the platform.

At each station surface sediments (0-2 cm) were collected by box-corer. Sediments were analysed for their particle size and organic matter content (OM). In addition the concentration of aluminium (Al), cadmium (Cd), chromium (Cr), barium (Ba), cuprum (Cu), mercury (Hg), nickel (Ni), lead (Pb), zinc (Zn) and polycyclic aromatic hydrocarbons (PAH) were measured.

Analytical techniques

Sediment samples were analysed for their particle size according to the Udden-Wentworth Phi classification (Wentworth, 1922). Each sample was washed in 16% hydrogen peroxide for 24 hours and then was wet sieved on a 63 μm mesh to sort out the fine fraction. The sand fraction was sieved through a stack of geological test-sieves ranging from 0 Phi to +4 Phi. The fine fraction was analysed by a sedigraph.

Organic matter content was determined by Loss On Ignition method (LOI). 3 g of dried (40°C for 48 hours) sediment samples were placed in the furnace and kept at 400°C for 12 hours. After cooling the percentage of the dry weight lost was calculated.

Heavy metal analysis was carried out digesting 0.5 g of fresh sediment in Teflon vessels with a mixture of concentrated HNO_3, HCl and HF (suprapur). The digestion was performed by a microwave digester. Hydrofluoric acid was neutralized by adding a saturated solution of boric acid. The analyses were performed by graphite furnace absorption spectrometry (Cd and Pb), atomic emission spectrometry (ICP AES) (Cu, Cr, Al, Zn and Ni) and cold vapour atomic absorption spectrometry after reduction by stannous chloride (Hg). Water content was determined by weight loss at 105°C. Concentrations were expressed as mg/kg dry weight, but Al was expressed as percentage. The accuracy of the analytical methods was checked analysing the certified reference materials PACS-2 Harbour sediment and MESS-3 Estuarine sediments (National Research Council Canada). The accuracy (as percentage recovery with respect to the certified value) ranged from 95% to 103%.

To determine the concentration of total polycyclic aromatic hydrocarbons (16 PAHs: Nap, Acl, Ace, Flu, Phe, Ant, Flt, Pyr, BA, Chr, B(*b*)F, B(*k*)F, BP, IP, dBA, BPer) 20 g wet weight subsample was extracted using methanol/benzen (1:1 v/v). Two other extractions were sequentially carried out using 50 ml of benzene. The extracts were then pooled and dried. The samples were analysed by HPLC after adding acetous-nitrile.

Data analysis

The matrix including heavy metals, organic matter content, total polycyclic aromatic hydrocarbons and percentage of clay was subjected to the Principal Components Analysis (PCA) performed on a correlation matrix using Brodgard software package (© Highland Statistics Ltd) to create composite variables (principal components) summarizing the sediment quality data. Prior to analysis data were examined for co-linearity. Since no significant co-linearity occurred, all contaminants were included into the matrix. Percentages of sand and silt were removed being not independent from clay.

The Trellis graphs were used to investigate the temporal trends of each contaminant comparing treatments and controls. These graphs were chosen because they allow to highlight the relationships between two variables (*i.e.* contaminants and time) conditional on other nominal variable (treatment/control).

The differences between treatment and control were tested by the non-parametric Kruskal-Wallis test being violated the variance homogeneity assumption for the Anova test. The level of significance was set at 0.05.

RESULTS

Sediment description: grain size and organic matter

Most of sediments collected along the two transects were brown or tan, without peculiar smell or black anoxic trails along the sedimentary profile. The oxidized superficial stratum varied between 1.5 and 2 cm. Signs of bioturbation, commonly observed, were mainly due to polychaete activity. The same macroscopic characteristics were observed in sediments collected at C sites. Bentonite clays and black anoxic trails were observed during the first two cruises in sediments under PC and at 30-60 m from it.

Grain size analysis revealed that most of the sediments consisted of mud (silt + clay) with a low percentage of sand (Tab. 1). Both at T and C sites the sand percentage was slightly higher in samples collected during winter periods than in those sampled in summer. The opposite pattern was observed for the fine fractions. These observations were consistent through time, but the differences were never statistically significant.

A significant difference was detected in 2003, when the clay percentage increased, both at T (H_{5vs11} = 18.0, p = 0.00) and C sites (H_{5vs11} = 3.85, p = 0.04), from the first (5 months after the end of the drilling operations) to the second sampling (11 months after), carried out respectively in winter and in summer.

Organic matter percentage varied in a narrow range from 2002 to the first sampling of 2004 (18 months after the end of the drilling operations) being included between 1% and 2.3% (Tab. 1). A significant increase of organic matter was observed 24 months after the end of the drilling operations both at T (H_{18vs24} = 2.47, p = 0.00) and C sites (H_{18vs24} = 3.91, p = 0.04). No other significant differences were detected either between T and C sites or between two consecutive field cruises in the remaining period.

Tab. 1 - Metal concentrations: Al (%), others mg/kg; total polycyclic aromatic hydrocarbons (mg/kg); grain size and organic matter (%).

	Al	**Ba**	**Cd**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Zn**	**OM**	**Sand**	**Silt**	**Clay**	**PAH**
2002 - 1 months after														
A1	6.7	281.0	0.180	101.6	16.7	0.13	61.8	21.9	81.3	1.45	1.4	43.7	54.9	2.456
A2	7.2	291.5	0.160	105.5	16.8	0.13	62.0	20.6	83.8	1.51	4.2	39.8	56.0	0.514
A3	7.9	711.5	0.160	105.8	17.1	0.13	65.1	21.4	86.2	1.56	4.0	39.9	56.1	0.990
A4	6.5	345.5	0.260	93.1	15.8	0.13	59.2	18.8	79.7	1.73	7.1	41.0	49.1	0.797
A5	7.6	1968.1	0.160	102.1	15.8	0.12	63.1	19.4	81.2	1.46	4.1	40.0	55.9	3.192
A6	7.8	524.3	0.170	104.8	16.6	0.13	64.7	20.8	84.2	1.51	3.0	43.3	53.7	2.384
A7	6.8	559.0	0.160	99.3	16.2	0.11	60.2	18.9	81.5	1.77	3.1	40.4	56.5	1.309
A8	7.4	283.7	0.140	104.3	15.3	0.13	64.2	22.2	82.2	2.04	3.2	38.5	58.4	1.396
A9	8.1	321.5	0.180	112.3	17.7	0.21	68.9	25.8	93.8	1.56	2.2	40.6	57.3	0.909
B1	6.6	481.3	0.120	109.4	17.1	0.14	67.8	24.8	90.2	1.74	2.9	39.7	57.5	1.382
B2	7.0	286.8	0.130	116.7	17.1	0.14	71.4	26.3	97.5	1.48	2.4	39.0	58.6	0.825
B3	8.0	277.9	0.130	109.1	16.7	0.12	67.2	25.3	90.0	1.07	3.1	38.7	58.3	2.915
B4	6.9	288.9	0.130	110.8	16.9	0.11	67.4	25.8	90.9	1.63	3.1	42.1	54.8	1.245
B5	7.2	588.1	0.130	114.7	18.0	0.13	71.9	28.7	94.6	1.32	3.1	45.0	51.9	0.445
B6	7.1	286.9	0.210	112.2	16.8	0.11	68.7	25.3	90.6	1.71	3.1	40.5	56.5	0.684
B7	7.4	271.3	0.130	113	17.6	0.11	68.0	27.5	92.8	1.39	3.2	40.0	56.8	1.953
B8	7.8	287.1	0.120	114.3	16.8	0.12	71.2	27.5	96.4	1.72	3.8	40.1	56.1	1.149
C1	6.0	207.7	0.110	111.3	16.4	0.12	69.5	38.6	90.5	2.3	2.6	43.7	53.7	0.566
C2	6.7	227.2	0.110	111.1	16.5	0.09	69.7	26.3	90.0	1.93	5.0	40.0	55.1	0.629
C3	6.9	232.5	0.110	116.1	17.1	0.10	72.8	25.2	92.2	1	2.6	44.7	52.7	0.292
2003 - 5 months after														
A1	5.4	225.5	0.130	87.6	17.7	0.15	56.4	21.2	73.6	1.51	4.8	50.1	45.1	0.743
A2	5.9	235.5	0.130	95.3	25.0	0.17	59.6	33.9	84.5	1.24	3.9	49.7	46.4	0.697
A3	5.8	294.3	0.130	95.7	20.3	0.07	61.6	23.6	83.2	1.41	4.2	50.8	45.0	0.731
A4	5.8	249.6	0.130	91	18.4	0.10	57.3	19.8	76.6	1.83	3.7	50.3	46.0	0.327
A5	5.6	272.1	0.120	92.8	19.2	0.10	59.2	20.8	84.4	1.33	4.0	50.8	45.2	0.412
A6	5.6	734.4	0.110	93.8	19.6	0.12	57.8	20.4	80.4	1.26	4.0	49.8	46.1	0.350
A7	5.4	268.4	0.110	88.1	17.8	0.12	59.8	20.4	78.0	1.27	4.1	48.8	47.1	0.418
A8	5.3	288.0	0.100	88	18.6	0.12	59.4	19.9	77.1	1.3	4.6	48.4	46.9	0.240
A9	5.4	323.5	0.100	89.9	18.5	0.14	57.9	43.6	78.8	1.56	3.3	50.6	46.1	0.580
B1	5.6	226.9	0.090	91.2	18.2	0.12	61.9	19.7	79.6	1.33	4.4	48.7	46.9	0.446
B2	5.5	313.4	0.090	92.8	18.2	0.10	58.3	15.8	75.2	1.06	3.1	49.4	47.5	0.572
B3	6.3	551.9	0.140	97.8	20.3	0.17	58.2	21.2	91.8	1.08	7.0	51.9	41.0	0.547
B4	5.5	338.6	0.100	95.1	21.1	0.18	59.6	28.5	85.4	1.27	3.4	54.5	42.1	0.596
B5	5.7	262.2	0.110	99.3	19.1	0.23	61.1	18.2	86.6	1.34	3.2	50.2	46.6	0.652
B6	5.6	365.2	0.130	95.7	28.2	0.18	58.6	17.2	85.0	1.08	3.1	53.8	43.1	0.479
B7	5.7	219.2	0.120	97.8	19.6	0.20	60.1	20.0	85.7	1.37	5.0	52.6	42.5	0.451
B8	5.6	199.8	0.110	94.5	18.8	0.17	60.4	16.1	80.7	1.37	4.5	49.8	45.6	0.254
C1	5.6	193.9	0.130	93.7	18.5	0.14	57.5	18.4	82.5	1.3	3.3	49.1	47.6	0.486
C2	5.5	191.0	0.110	96.9	18.9	0.14	58.4	18.3	84.8	1.2	3.9	49.9	46.1	0.417
C3	5.5	192.5	0.100	94	18.3	0.17	58.7	18.3	81.5	1.24	3.6	50.4	46.0	0.356

	Al	Ba	Cd	Cr	Cu	Hg	Ni	Pb	Zn	OM	Sand	Silt	Clay	PAH
2003 - 11 months after														
A1	5.6	341.5	0.060	101.2	26.8	0.10	71.2	41.5	92.8	1.89	2.2	37.2	60.6	0.807
A2	8.4	2817.9	0.080	146.3	37.5	0.12	96.0	59.2	140.1	1.55	1.8	46.2	52.0	0.664
A3	5.6	4081.8	0.070	101.4	29.7	0.11	72.3	47.5	101.8	1.3	4.0	53.5	42.5	0.573
A4	4.8	3758.7	0.070	85.23	26.7	0.34	56.4	38.9	87.0	1.18	6.0	42.7	51.3	0.434
A5	4.7	514.0	0.060	81.86	18.7	0.17	58.4	32.0	95.8	1.17	4.1	42.4	53.5	0.357
A6	5.1	341.2	0.050	90.22	21.0	0.14	58.9	31.4	90.0	1.52	3.0	43.7	53.3	0.352
A7	4.6	523.3	0.050	80.49	20.7	0.15	61.1	33.3	89.0	1.4	2.4	47.2	50.4	0.357
A8	5.1	434.9	0.050	90.51	19.3	0.11	57.0	31.8	86.4	1.39	2.7	50.9	46.4	0.337
A9	5.1	311.1	0.050	91.78	19.7	0.12	58.3	32.1	85.6	1.28	1.8	43.8	54.3	0.279
B1	4.7	244.3	0.070	83.88	18.1	0.17	58.9	32.2	74.1	1.29	2.6	45.1	52.3	0.615
B2	4.4	486.0	0.090	84.02	18.9	0.14	55.0	31.9	79.6	1.43	2.5	47.1	50.4	0.455
B3	4.8	362.1	0.090	87.44	18.9	0.07	58.1	40.8	81.6	1.13	2.1	42.1	55.8	0.524
B4	5.1	633.8	0.080	92.72	33.1	0.08	58.7	74.7	122.3	1.46	2.7	46.4	50.9	0.468
B5	4.8	279.4	0.120	85.41	18.0	0.10	59.3	29.9	75.9	1.2	2.6	43.9	53.5	0.439
B6	4.6	264.8	0.090	83.71	18.1	0.15	57.0	30.6	76.9	1.15	2.9	44.2	52.9	0.480
B7	5.3	279.5	0.090	95.76	19.2	0.16	59.8	30.7	84.0	1.12	2.2	49.5	48.3	0.372
B8	5.2	266.6	0.140	98.02	20.5	0.16	63.7	34.9	87.9	1.2	2.2	50.8	47.0	0.419
C1	4.7	228.7	0.090	87.17	18.1	0.20	57.3	30.9	77.9	1.23	2.5	47.3	50.2	0.417
C2	4.6	235.0	0.110	83.33	18.3	0.10	56.2	27.4	80.0	1.3	3.4	48.8	47.8	0.436
C3	5.1	232.2	0.080	89.46	17.9	0.15	58.1	29.8	79.0	1.29	2.5	48.3	49.2	0.300
2004 - 18 months after														
A1	7.0	448.2	0.090	121.2	22.6	0.00	64.4	25.8	123.8	1.56	1.8	39.5	58.7	0.338
A2	6.1	315.8	0.090	112.1	20.6	0.00	65.0	23.7	135.0	1.18	2.4	45.4	52.1	0.344
A3	6.3	368.2	0.090	106.9	21.8	0.07	63.6	23.8	130.8	1.22	2.6	43.6	53.8	0.446
A4	5.8	333.0	0.080	98.77	19.7	0.00	61.7	22.3	130.3	1.49	3.1	42.8	54.2	0.314
A5	6.1	385.5	0.090	101	17.8	0.00	61.4	23.2	133.3	1.3	3.3	41.1	55.7	0.370
A6	6.1	731.1	0.080	100.7	19.2	0.05	61.6	27.0	103.9	1.39	3.3	44.6	52.2	0.294
A7	6.2	320.3	0.090	102.3	18.8	0.05	64.0	23.5	98.8	1.06	3.3	44.0	52.7	0.204
A8	6.2	335.5	0.080	106.2	19.7	0.00	61.4	25.1	99.8	1.57	3.3	42.3	54.3	0.186
A9	5.7	226.2	0.080	94.8	15.1	0.00	59.0	19.5	78.0	1.02	4.5	45.6	49.9	0.225
B1	6.6	349.0	0.080	109.2	20.1	0.00	64.1	23.1	107.9	1.13	3.0	41.7	55.4	0.236
B2	5.8	549.6	0.070	99.28	19.9	0.00	63.2	27.0	103.8	1.07	3.2	41.2	55.6	0.265
B3	5.3	712.1	0.070	85.47	14.5	0.00	52.1	25.3	77.7	1.37	10.3	40.6	49.1	0.361
B4	5.7	928.2	0.080	98.19	41.1	0.00	58.3	38.8	117.1	1.28	7.1	39.6	53.3	0.545
B5	6.2	514.7	0.080	100.8	19.1	0.00	63.4	23.1	99.0	1.08	3.9	43.3	52.7	0.337
B6	6.1	296.8	0.080	100.2	19.6	0.04	64.7	26.3	96.9	1	3.2	40.3	56.5	0.293
B7	6.4	293.0	0.070	107.3	19.4	0.00	64.4	23.8	100.0	1.22	2.4	41.7	55.9	0.297
B8	5.7	261.5	0.080	106.4	19.5	0.00	61.5	22.8	100.6	1.03	3.4	43.8	52.8	0.095
C1	6.1	259.1	0.080	105.1	19.5	0.00	62.1	21.3	100.3	1.04	4.0	45.2	50.8	0.277
C2	6.0	242.5	0.080	99.13	18.0	0.05	59.2	21.2	93.6	1.31	4.1	44.5	51.4	0.193
C3	6.5	260.2	0.080	112.5	20.3	0.04	66.6	20.7	106.5	1.37	1.8	47.7	50.5	0.216

	Al	Ba	Cd	Cr	Cu	Hg	Ni	Pb	Zn	OM	Sand	Silt	Clay	PAH
2004 - 24 months after														
A1	7.4	236.6	0.076	107.1	23.1	0.05	45.6	28.3	88.2	2.63	1.8	38.0	60.2	0.567
A2	2.8	1073.1	0.076	105.8	29.1	0.05	49.6	29.2	89.3	2.55	2.6	40.7	56.7	0.446
A3	7.7	1742.6	0.080	101.4	24.9	0.04	44.4	31.5	86.6	2.98	6.1	43.0	50.9	0.464
A4	6.6	3073.7	0.098	91.38	36.7	0.08	39.9	41.0	128.4	2.63	6.4	45.4	48.2	1.340
A5	6.2	1364.1	0.098	105.6	55.5	0.04	52.0	38.1	119.4	2.95	6.0	44.9	49.1	0.746
A6	5.8	611.8	0.082	96.99	21.9	0.03	48.9	29.1	120.9	3.87	6.0	40.7	53.4	0.538
A7	5.1	693.5	0.106	104	22.6	0.06	50.7	27.6	88.7	3.3	3.9	44.0	52.1	0.418
A8	6.6	304.0	0.066	111	19.1	0.10	52.6	27.7	94.7	3.47	3.2	42.5	54.3	0.274
A9	5.2	317.4	0.066	114.3	19.6	0.00	55.5	30.2	93.4	3.78	1.8	40.6	57.6	0.397
B1	6.3	210.5	0.068	111.7	18.4	0.06	55.6	28.6	92.6	3.69	3.0	41.9	55.1	0.310
B2	4.9	381.4	0.064	112.2	18.9	0.03	54.0	28.3	91.8	3.67	2.5	43.8	53.8	0.364
B3	6.1	375.6	0.078	110.5	20.6	0.03	52.2	28.8	90.5	3.19	3.5	43.9	52.3	0.343
B4	5.4	325.7	0.072	80.47	19.3	0.04	51.8	33.7	132.0	3.49	4.5	43.5	52.0	0.636
B5	6.9	145.2	0.062	108.7	16.6	0.02	54.4	39.5	126.5	3.24	3.1	44.2	52.7	0.419
B6	4.4	425.4	0.092	109	18.9	0.02	56.1	28.4	90.8	2.97	2.7	44.4	52.9	0.381
B7	4.7	216.0	0.074	105.6	19.6	0.04	53.2	29.4	88.5	3.19	2.9	43.6	53.6	0.188
B8	6.1	210.0	0.060	113.7	18.8	0.04	55.1	30.6	91.5	2.86	2.0	42.0	56.0	0.214
C1	6.4	1094.1	0.068	111.9	19.2	0.04	53.9	29.6	88.0	3.07	2.4	46.3	51.3	0.259
C2	4.3	159.2	0.100	107	18.5	0.04	53.8	28.8	87.7	2.54	3.4	46.5	50.1	0.272
C3	5.2	158.0	0.082	108.1	18.3	0.03	53.5	28.5	87.9	2.57	2.1	44.6	53.5	0.246
2005 - 30 months after														
A1	6.1	620.0	0.060	112.63	9.9	0.03	65.2	26.7	78.9	2.66	2.3	43.4	54.4	0.343
A2	6.1	637.7	0.042	110.45	14.3	0.03	64.4	36.4	78.9	2.49	2.0	48.4	49.6	0.278
A3	5.9	1072.6	0.053	106.69	14.0	0.05	62.5	27.0	80.4	2.78	2.8	45.9	51.3	0.204
A4	5.3	557.8	0.049	97.91	29.6	0.03	57.5	24.7	75.7	2.56	4.3	45.0	50.7	0.189
A5	4.9	294.6	0.061	101.83	13.1	0.03	58.1	20.7	109.3	2.74	5.3	47.7	47.0	0.492
A6	5.0	236.5	0.055	99.81	10.5	0.01	59.1	15.2	66.5	2.53	2.9	48.8	48.4	0.325
A7	5.1	654.4	0.072	99.37	16.1	0.06	60.6	40.6	78.0	3.20	3.9	47.3	48.8	0.342
A8	5.7	319.4	0.036	108.49	12.7	0.05	60.9	13.9	77.4	2.15	6.8	41.6	51.6	0.307
A9	6.0	489.9	0.055	110.45	12.3	0.03	63.2	20.9	79.7	1.91	1.2	42.6	56.2	0.378
B1	6.0	1311.0	0.050	109.49	12.9	0.08	65.7	42.7	81.8	2.47	2.1	47.0	50.9	0.201
B2	5.7	336.5	0.040	106.36	13.0	0.03	64.6	50.7	80.2	2.32	2.9	38.3	58.8	0.232
B3	5.6	731.9	0.032	103.00	32.3	0.03	58.1	54.2	74.4	1.96	6.0	49.1	44.9	0.201
B4	5.2	1007.7	0.046	103.30	16.8	0.03	60.7	46.2	85.6	2.53	4.0	45.4	50.6	0.303
B5	4.4	555.6	0.075	102.28	12.4	0.02	61.2	37.1	78.2	2.64	2.7	45.7	51.6	0.176
B6	5.8	305.3	0.048	108.86	14.0	0.05	63.6	40.6	87.8	2.83	3.0	41.3	55.7	0.318
B7	4.9	507.0	0.067	104.27	12.9	0.02	62.1	37.1	79.0	3.17	2.1	46.1	51.8	0.315
B8	4.3	2258.9	0.084	110.70	13.6	0.02	66.4	18.6	89.7	3.01	1.8	40.9	57.3	0.307
C1	5.2	230.8	0.064	102.63	11.4	0.02	60.8	19.1	78.0	3.16	2.3	53.1	44.6	0.244
C2	4.6	585.7	0.078	110.16	13.4	0.02	63.9	18.5	80.3	3.36	3.0	50.6	46.4	0.265
C3	5.0	215.7	0.054	99.39	11.3	0.03	58.0	17.0	76.3	3.17	3.3	53.4	43.2	0.303

	Al	Ba	Cd	Cr	Cu	Hg	Ni	Pb	Zn	OM	Sand	Silt	Clay	PAH
2005 - 36 months after														
A1	3.5	323.8	0.012	78.08	3.6	0.08	38.9	24.7	63.2	2.00	3.0	42.5	54.4	0.430
A2	4.5	611.3	0.012	109.47	5.2	0.08	53.5	26.4	97.6	2.08	2.0	41.3	56.8	0.246
A3	6.0	766.5	0.036	153.97	14.5	0.10	75.2	17.6	163.8	2.29	2.7	43.4	53.9	0.178
A4	5.4	378.3	0.024	125.02	15.0	0.07	61.6	30.1	150.8	2.18	4.9	44.5	50.7	0.166
A5	4.7	1370.2	0.048	105.50	15.0	0.10	59.2	21.2	87.3	3.02	5.4	44.1	50.5	0.205
A6	4.2	1251.4	0.024	107.68	32.3	0.07	51.8	26.5	174.8	2.68	2.3	43.1	54.6	0.242
A7	3.9	377.7	0.060	85.57	6.2	0.09	25.6	27.9	61.6	3.02	3.3	45.8	50.9	0.230
A8	4.9	413.3	0.048	113.77	10.0	0.09	41.6	25.0	98.7	2.74	2.7	44.3	53.0	0.230
A9	4.2	514.6	0.072	124.02	6.9	0.07	47.7	27.0	121.0	3.12	1.7	44.7	53.7	0.316
B1	4.3	346.1	0.048	139.81	4.1	0.08	64.5	28.6	117.0	2.93	3.0	44.1	52.9	0.108
B2	4.2	444.0	0.060	141.58	5.7	0.07	63.4	27.1	128.1	3.28	2.2	46.8	51.0	0.160
B3	4.1	1172.8	0.060	130.79	8.8	0.07	60.3	28.0	142.1	3.43	2.7	46.3	51.1	0.160
B4	3.6	1450.5	0.060	146.40	26.3	0.07	71.9	24.5	151.6	3.71	5.4	43.4	51.2	0.222
B5	4.1	416.3	0.036	135.98	3.4	0.07	83.0	23.3	124.3	3.43	2.7	43.2	54.1	0.164
B6	3.9	164.3	0.036	152.24	4.8	0.10	88.6	27.8	122.1	2.88	2.7	44.1	53.3	0.255
B7	4.3	366.0	0.024	143.47	5.5	0.07	83.8	26.2	107.9	3.21	1.9	43.0	55.1	0.275
B8	4.6	355.0	0.024	159.30	4.7	0.09	92.5	21.3	120.6	2.54	2.0	45.0	53.0	0.186
C1	5.3	332.2	0.024	153.26	2.6	0.09	88.6	24.6	119.7	2.42	2.3	48.5	49.1	0.236
C2	3.5	250.7	0.024	127.15	4.3	0.06	73.4	16.6	88.9	2.85	2.9	48.3	48.9	0.284
C3	4.2	319.3	0.024	155.65	5.1	0.08	93.6	26.3	115.0	2.19	2.2	46.0	51.8	0.304

Multivariate analysis: principal component analysis

In the Principal Components Analysis the first three axes accounted for 58.2% of the total variance (25%, 17.6%, 15.6% respectively). The plot of the first two principal components (Fig. 2a) showed that most of the T-points were included in a cloud located near the origin of the axes. In addition, the samples on the left of the ordination plot were collected during the first field cruise (1 month after drilling ceased), while those collected during the last cruise (36 months after drilling ceased) were located at the opposite side of the plot.

The second axis split up the station A2 (sampled 11 months after the end of the drilling operations) located 120 m far from the platform from the stations A1 and A7 (sampled 36 months after the end of the drilling operations).

The third axis (Fig. 2b) split up some stations sampled 11 and 24 months after the end of the drilling operations from the cloud of the other stations.

The ordination of the samples collected in 2002 along the first axis of the PCA was due to the high concentrations of Cd, Al, Hg, PAH (Tab. 1) as suggested by the factor loadings of these contaminants (Tab. 2)

The relative positions of the sample-points along the second axis were explained by the higher concentrations of Al, Cr, Ni at treatment A2.

The distribution of the stations along the third axis was due to anomalies of Cu, Pb, Ba detected 11 and 24 months after the end of the drilling operations.

The Kruskal Wallis test confirmed that the anomalies detected during the first cruise (2002) regarded PAH, Al, Cd, Hg, Ni and Ba, in fact the concentrations of these contaminants were significantly higher in T than in C (Tab. 3) although for some T stations the recorded values were only slightly different from C.

By contrast, a high level of disturbance was detected under the platform. Here the concentration of PAH (3.192 mg/kg) and Ba (1968.1 mg/kg) were, respectively, about 6 and 8 times higher (Tab. 1) than the average of the controls (PAH = 0.496 ± 0.17 mg/kg; Ba = 222.5 ± 13.1 mg/kg).

In the following samplings, on average, most of contaminants showed a general decreasing trend over time. This pattern was commonly observed for T and C sites (Fig. 3). The opposite trend was observed only for Cr, Ni, and organic matter (Fig. 3).

However, some signals of disturbance were detected, over the monitoring program, although limited to a few stations. The anomalies regarded almost all contaminants, but more frequently Cu, Pb, Ba, and Zn (Tab. 1).

Even at the end of the monitoring assessment, that is three years (last sampling in 2005) after the end of the drilling operations some effects of the platforms were still detectable.

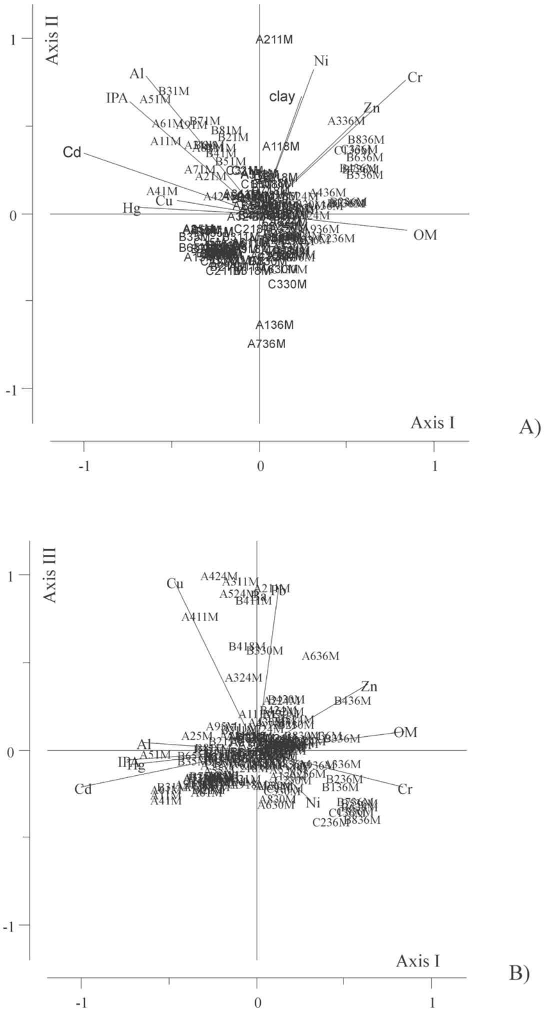

Fig. 2 - Principal component analysis (PCA). I and II axis (A); I and III axis (B). Labels: the first letter and the number indicates the site, the second figure followed by M indicates the months after the end of the drilling operations. For explanatory variables see «Materials and methods».

Tab. 2 - Factor loadings of each variable extracted by Principal Component Analysis.

	Axis I	Axis II	Axis III
Al	-0.299	-0.432	-0.024
Ba	0.004	-0.126	-0.52
Cd	-0.462	-0.188	0.123
Cr	0.39	-0.421	0.129
Cu	-0.216	-0.041	-0.563
Hg	-0.322	-0.021	0.053
Ni	0.143	-0.456	0.174
Pb	0.058	-0.031	-0.54
Zn	0.297	-0.336	-0.218
OM	0.392	0.053	-0.062
Clay	0.113	-0.366	0.044
PAH	-0.341	-0.352	0.036

The most relevant regarded Ba and Zn. The concentration of barium (1370.2 mg/kg) under the platform and at 30-60 m from it, was about 3-5 times the average concentration of the controls (300.7 ± 43,8 mg/kg). Zinc showed in the surroundings of the structure (30-60 meter apart) a concentration significantly higher than those of the controls (Kruskal-Wallis: $H = 4.5$, $p = 0.033$).

Conclusions

Sediments both at the T and the C sites mainly consisted of mud with a similar percentage of clay and silt. The construction of platform Calipso and its activity did not affect significantly the texture of the surrounding sediments. The trend toward an increasing of finer fractions generally observed during summer is more likely an effect related to the low hydrodynamic regime occurring during that season.

In general, the dynamics of the organic matter appeared not influenced by the structure and reflected a natural temporal variability.

Regarding PAHs and heavy metals the greatest impact occurred immediately after the drilling operations, whereas the following exploitation phase did not represent a consistent further source of disturbance.

In fact, the highest concentrations of contaminants were detected during the first survey carried out about one month after the end of drilling operations. Signs of disturbance were observed in almost all sediments surrounding the platform suggesting a spread alteration of the area.

In particular, the contents of PAHs determined in the sediments close to the platform were 10 times higher if compared to the average concentrations reported by Magi *et al.* (2002) for the coastal marine area off Ancona.

During the following surveys recovery clues were observed as a general decreasing trend of most contaminants. However, few signs of stress were locally detected although they do not follow linear spatial or temporal gradients. This is likely due to the complexity of dispersion mechanisms that are compelled by sediment heterogeneity and by variability of microscale hydrodynamic processes. Longer recovery time was observed for barium and zinc that showed significant anomalies till the end of the monitoring program. Anomalies concerning barium are not surprising because it is a constituent of the barite commonly used in drilling muds (Steinhauer *et al.*, 1994), the most probable source of this metal.

Persistent anomalies of zinc are not a novel in the Adriatic Sea. Recently a similar situation has been docu-

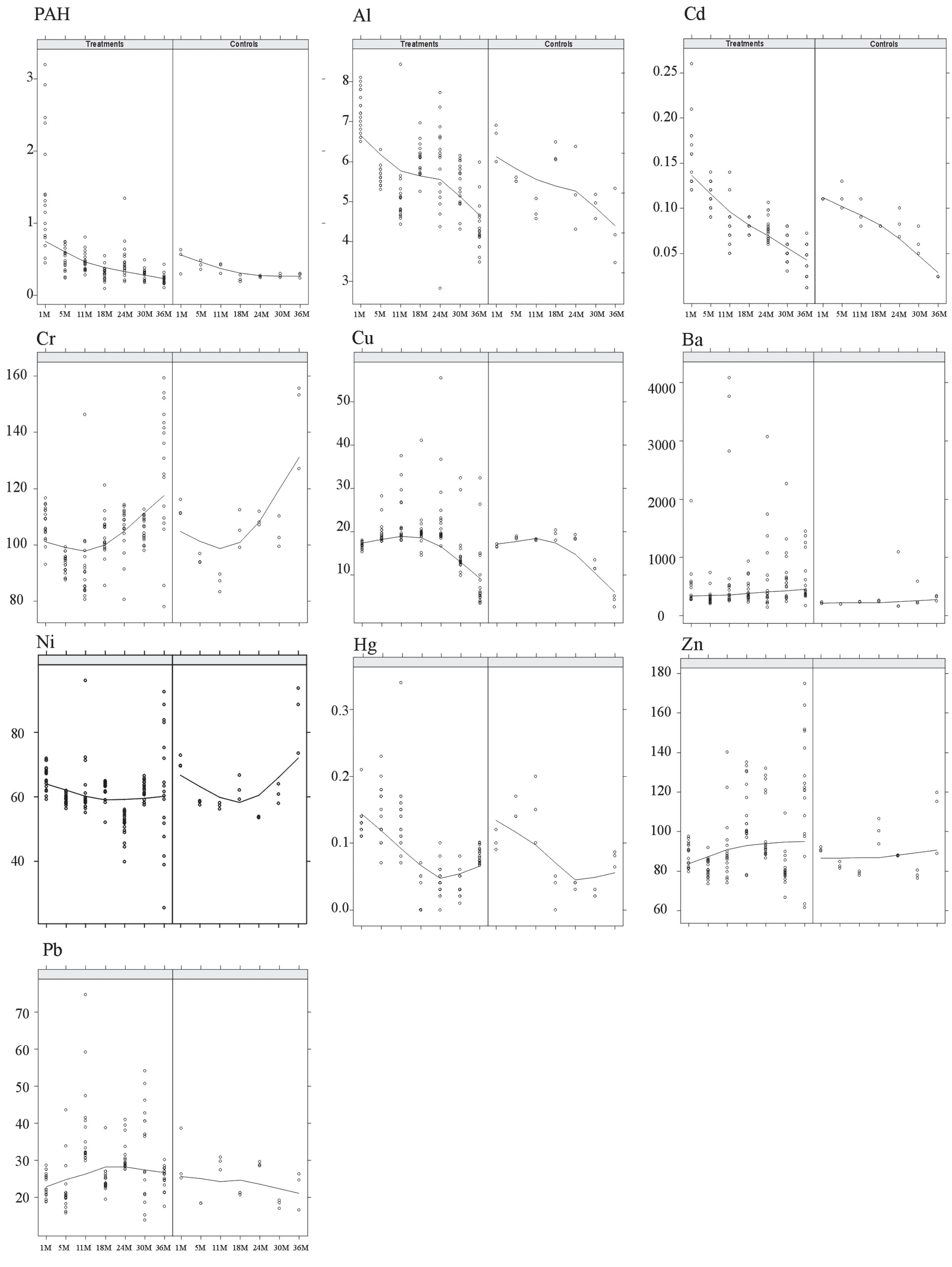

Fig. 3 - Trellis graphs for each contaminant.

Tab. 3 - Kruskal-Wallis test T *vs*. C for each sampling occasion. In each column H,p are indicated. Significant values are in bold. First row indicates the sampling year. Samples were collected 1 … 36 months after the end of the drilling operations (second row).

	2002	**2003**		**2004**		**2005**	
	1	**5**	**11**	**18**	**24**	**30**	**36**
PAH	**5.17; 0.02**	0.63; 0.42	1.23; 0.26	2.35; 0.124	**4.26; 0.039**	0.40; 0.52	2.69; 0.10
Al	**3.85; 0.049**	**0.57; 0.044**	1.75; 0.53	0.025; 0.87	0.63;0.42	2.04; 0.15	0.13; 0.71
Ba	**7.28; 0.007**	7.28; 0.07	**7.28; 0.007**	**5.67; 0.017**	1.10; 0.31	3.05; 0.08	**5.17; 0.022**
Cd	**7.49; 0.006**	0.026; 0.87	1.80; 0.17	0.13; 0.71	0.81; 0.36	1.75; 0.18	2.16; 0.14
Cr	1.75; 0.18	0.34; 0.56	0.80; 0.36	0.22; 0.63	0.33; 0.56	0.33; 0.56	2.04; 0.15
Cu	0.283; 0.59	0.72; 0.39	**4.26; 0.03**	0.07; 0.79	3.05; 0.08	1.75; 0.18	3.43; 0.06
Hg	**4.75; 0.02**	0.10; 0.74	0.22; 0.41	1.54; 0.21	0.63; 0.42	2,04; 0.15	0.22; 0.63
Ni	**4.26; 0.03**	1.23; 0.26	2.69; 0.10	0.70; 0.79	0.63; 0.42	0.47; 0.49	**4.26; 0.039**
Pb	2.20; 0.13	2.04; 0.15	**5.67; 0.017**	5.67; 0.017	0.17; 0.67	3.83; 0.051	1.75; 0.18
Zn	0.28; 0.59	0.226; 0.63	2.69; 0.10	0.47; 0.49	**5.67; 0.017**	0.63; 0.42	1.01; 0.31

mented at Regina and Annalisa platforms (Ferrari *et al*., 2002; De Biasi *et al*., 2006). Also previous studies detected anomalous concentration of zinc in mussels, both in their soft parts and in their shells, collected near the anodes of the platform Antares (Mauri *et al*., 1998) situated about 10 km off Ravenna harbour (North Adriatic Sea) on a silty clay bottom at 15 meters depth. According to these authors the sacrificial anodes, which are the corrosion protection system for the submerged parts of platforms, provided a large quantity of this metal. This explanation is not suitable to interpret the results regarding Calipso as well as those obtained on platforms Regina and Annalisa because the anodes used in these cases are mainly constituted by magnesium and aluminium, whereas zinc is present in a very low percentage. Hence, this result warrants further studies and suggests that even in the case of Antares the anodes could not have been the unique source of zinc.

Summarising the clearest signs of impact were related to the installation phase and the end of drilling operations. Three years after, most of anomalies were attenuated and no significant differences in contaminant concentrations were detected between T and C. Hence 3-year can be considered a good estimate of the recovery time of the abiotic compartment.

Although different spatial and temporal trends were observed for Annalisa (De Biasi *et al*., 2006), Regina (Ferrari *et al*., 2002) and Barbara (Fabi *et al*., 2005) a 3-year period can be considered a sufficient time lag to re-establish a natural abiotic situation in the surroundings of these platforms.

Even for Antares chemical contaminant anomalies attenuated after the end of discharges, but with longer recovery processes. In addition the anomalies of Cr and Pb detected in the case of Antares, were more limited in the case of Calipso.

By contrast the anomalies regarding Zn and Ba were commonly observed for all these platforms and they did not recovery within 3 years. In Antares signs of contamination by these metals were still detected after 6-7 years.

These recovery times observed in the Adriatic Sea can not be compared with those reported for platforms operating in the North Sea or the Gulf of Mexico having different dimensions and drilling methods.

However, even in these cases chemical contaminants originate from the drilling mud discharge and not from production irrespective to the characteristics of the platform itself (Montagna & Harper, 1996; Peterson *et al*., 1996).

These results should be taken into account to improve the mitigation measures and make them more effective on limiting environmental impacts.

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References

Auger C.P., 1998. Information sources in grey literature. 4th Eds. Bowker Saur., London.

Breuer E., Stevenson A.G., Howe J.A., Carroll J.A, Shimmield G.B., 2004. Drill cutting accumulations in the Northern and Central North Sea: a review of environmental interaction and chemical fate. *Mar. Poll. Bull*. 48: 12-25.

Bombace G., Fabi G., Rivas G., 1999. Effetti sul popolamento ittico indotti da una piattaforma estrattiva dell'alto Adriatico: prospettive di gestione delle risorse costiere. *Biol. Mar. Medit*. 6: 64-72.

Cattaneo A., Correggiati A., Langone R., Trincardi F., 2003. The late-Holocene Gargano subaqueous delta Adriatic shelf: sediment pathways and supply fluctuations. *Mar. Geol*. 193: 61-91.

De Biasi A.M., Fabi G., Pacciardi L., Gai F., Ferrari S., Puletti M., De Ranieri S., 2006. Monitoraggio di una piattaforma di estrazione nel Mar Adriatico settentrionale: metalli pesanti. *Atti Soc. tosc. Sci. nat., Mem., Serie B* 113: 83-89.

Ellis J.I., Schneider D.C., 1997. Evaluation of a gradient sampling design for environmental impact assessment. *Environ. Monit. Ass.* 48: 157-172.

Fabi G., Ausili S., Campanelli A., De Biasi A., Fornasiero P., Grati F., Grilli F., Marini M., Panfili M., Paschini E., Puletti M., Scarcella G., Spagnolo A., 2005. Methods of assessing the ecological impact of gas platforms in the Adriatic Sea: two different scenarios. (In Libro de Ponencias II Congreso Internacional de Ciencia y Tecnología Marina - Oceanos III Millennium, Tomo I. (pp. 127-139) Editorial C.P.D., Madrid.)

Fabi G., Grati F., Lucchetti A., Trovatelli L., 2002. Evolution of fish assemblage around a gas-platform in the northern Adriatic Sea. *ICES J. Mar. Sc.* 59 (suppl): 309-315.

Fabi G., Grati F., Puletti M., Scarcella G., 2004. Effects on fish community induced by installation of two gas platforms in the Adriatic Sea. *Mar. Ecol. Progr. Ser.* 273: 187-197.

Fabi G., Da Ros L., De Biasi A.M., Manoukian S., Nasci C., Puletti M., Punzo E., Spagnolo A., 2007. Environmental impact of gas platforms in the Northern Adriatic Sea: a case study. Rapports et procès-verbaux de la Commission internationale pour l'étude scientifique de la Mer Méditerranée, 38: 45.

Ferrari S., De Biasi A.M., Fabi G., Ceffa L., 2002. Metalli pesanti in sedimenti marini e organismi in prossimità di una piattaforma gas-metano posta nel Mar Adriatico Centrale. *Atti Soc. tosc. Sci. nat., Mem., Serie B* 109: 105-110.

Ferrari S., De Biasi A.M., Pacciardi L., Fabi G., Ceffa L., 2003. Bioaccumulo di metalli in tracce in *Mytilus galloprovincialis* prelevato sui *jacket* di una piattaforma gas-metano. *Atti Ass. It. Oceanol. Limnol.* 16: 115-120.

Ferrari S., De Biasi A.M., Pacciardi L., Fabi G., Puletti M., 2004. Impiego del biondicatore *Mytilus galloprovincialis* per la valutazione dei livelli di metalli pesanti nei pressi di una piattaforma di estrazione gas-metano. *Biol. Mar. Medit.* 11: 322-325.

Frascari F., Rosso G., Bortoluzzi G., Barbanti A., Ravaioli M., Bonvicini Pagliai A.M., Crema R., Castelli A., Mauri M., Zunarelli R., Orlando E., Prevedelli D., Ceffa L., Ratti S., 1991. Uno studio sull'impatto dell'attività di perforazione in ambiente marino. *Atti Società Italiana di Ecologia* (S.It.E.) 12: 761-767.

Frascari F., Rosso G., Bortoluzzi G., Barbanti A., Bonvicini Pagliai A.M., Crema R., Castelli A., Mauri M., Zunarelli R., Orlando E., Prevedelli D., Ceffa L., Ratti S., 1992. Environmental impact of water based drilling muds and cuttings in a northern Adriatic Sea site. *Bulletin de l'Institut Océanographique*, Monaco 11: 305-324.

Frascari F., Marcaccio M., Spagnoli F., Modica A., 2000. Effects of offshore drilling activities on the geochemical and sedimentological processes in the Northern Adriatic coastal area. *Period. Biol.* 102: 225-241.

Guerzoni S., Frignani M., Giordani P., Frascari F., 1984. Heavy metals in sediments from different environments of a Northern Adriatic Sea area, Italy. *Environ. Geol. Wat. Sc.* 6: 111-119.

Magi E., Bianco R., Ianni C., Di Carro M., 2002. Distribution of polycyclic aromatic hydrocarbons in the sediments of the Adriatic Sea. *Environ. Poll.* 119: 91-98.

Mauri M., Polimeri R., Modica A., Ferraro M., 1998. Heavy metal bioaccumulation associated with drilling and production activities in Middle Adriatic Sea. *Fres. Environ. Bull.* 7: 60-70.

Mauri M., Spagnoli F., Marcaccio M., 2004. Heavy metal in sediments and bioaccumulation in the Bivalve *Corbula gibba* in a drilling discharge area. *Annali di Chimica* 94: 57-69.

Modica A., Cannata S., Ceffa L., Frasari F., Froglia C., Crema R., Rivas G., 1998. Environmental impact assessment of AGIP offshore exploration and production activities in the Mediterranean. Results synthesis of field investigation carried out between 1986 and 1996. *Fres. Environ. Bull.* 7: 142-154.

Montagna P., Harper D.E. Jr., 1996. Benthic infaunal long-term response to offshore production platforms in the Gulf of Mexico. *Canadian J. Fish Aq. Sc.* 53: 2567-2588.

Olsgard F., Gray J.S., 1995. A comprehensive analysis of the effects of offshore oil and gas exploration and production on the benthic communities of the Norwegian continental shelf. *Mar. Ecol. Progr. Ser.* 122: 277-306.

Peterson C.H., Kennicutt M.C., Green R.H., Montagna P., Harper D.E., Powell E.N., Roscigno P.F., 1996. Ecological consequences of environmental perturbations associated with offshore hydrocarbon production: a perspective on long-term exposures in the Gulf of Mexico. *Canadian J. Fish Aq. Sc.* 53: 2637-2654.

Steinhauer M., Crecelius E., Steinhauer W., 1994. Temporal and spatial changes in the concentrations of hydrocarbons and trace metals in the vicinity of an off-shore oil-production platform. *Mar. Environ. Res.* 37: 129-163.

Wentworth C.K., 1922. A scale of grade and class terms for clastic sediments. *J. Geol.* 30: 377-392.

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