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Beach morphodynamics forcements in oiled shorelines: Coupled physical and chemical processes during and after fuel burial

A.M. Bernabeu [a,*], M. Nuez de la Fuente [a], D. Rey [a], B. Rubio [a], F. Vilas [a], R. Medina [b], M.E. González [b]

[a] *Marine and Environmental Geology Group (GEOMA), Dpto. de Geociencias Marinas y O. T., Universidad de Vigo, 36310 Vigo, Spain*
[b] *Ocean and Coastal Research Group (GIOC), Dpto. Ciencias y Técnicas el Agua y del M.A., Universidad de Cantabria, 39005 Santander, Spain*

Abstract

In November 2002, the sinking of the Prestige oil tanker off the Galician coast (N.W. Spain) caused the largest ecological catastrophe in the history of Spain, affecting the coast called the 'Costa da Morte' (Galicia, N.W. Spain).

This work is focused on the study of the oil contamination of the intertidal area of two beaches located on this stretch of coast. The study of twenty cores extracted from both beaches has identified fuel embedded in the sedimentary column up to a depth of 2.38 m (this being the maximum depth of extraction). This, along with the presence of oil below the groundwater indicates the existence of a new factor which determines the burial of oil: the morphodynamic behaviour of the beach. Furthermore, this morphodynamic variation conditions the physical appearance of the buried oil. Four different types have been identified: tar-balls (cm), particles (mm), oil coatings on sediment grains and on emulsion, with distribution patterns conditioned by the degree of wave exposure.

The analysis of the information obtained have permitted the development of a conceptual model of the burial and oil evolution in the sedimentary column in relation to wave exposure, and thus to the morphodynamic variability of the beach.

Keywords: Prestige; Oil spill; Intertidal beach zone; Beach morphodynamics; Oil burial; Mechanical degradation

1. Introduction

The sinking of the Prestige oil tanker off the Galician coast (N.W. Spain) on the 19th of November 2002 produced the largest ecological catastrophe in Spanish history. More than 70,000 tons of oil were spilled, of which 53,000 tons were retrieved in the open sea (AZTI report, 2003), and the remaining amount reached 1000 km of the North Atlantic coast of Spain and some parts of the French coast in different proportions. The Prestige spillage had a great social impact. Hundreds of thousands people from all over Spain volunteered to help in the cleaning process which took months. It also had a huge economic impact as it affected the fishing and marine cultivation on which this area depends economically. The environmental effect will have to be examined in the long term.

The characteristics of the oil transported by the Prestige have been defined in various works (CSIC report, 2002; LE CEDRE report, 2002; Albaigés and Bayona, 2003). It is a product with high density (0.99 g/cm) and viscosity (615 cSt at 50% and 30,000 cSt at 15%). Its elemental composition is made up of 85.8% carbon (C), 11% hydrogen (H), 2.28% sulphur (S) and 0.69% nitrogen (N), being made up of 22% saturated hydrocarbon, 50% aromatic hydrocarbon, and 28% resins and asphalts. The metal content was 55% nickel (Ni) and 170 mg/kg vanadium (V). Its ageing in the sea is characterised by a high tendency to form stable emulsions with water up to 50% of its weight and a minimum evaporation (2–5%) which is why its degradation in the sea is very slow. The described characteristics indicate a low capacity for penetration into the sediment once the oil has been removed (CSIC report, 2002). This

* Corresponding author. Fax: +34 986 812556.
E-mail address: bernabeu@uvigo.es (A.M. Bernabeu).

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corresponds with the works of other authors who establish that the depth and the penetration rate depend on the viscosity and volume of the oil as well as the porosity of the sediment (Owens, 1978; Santas and Santas, 2000). Thus the coarser the grain size, with larger intergranular spaces or pores, the faster the oil penetration. The existing estimates of the depth of the oil burial establish average values of 15–25 cm (Teal et al., 1978; Hayes et al., 1993) although a maximum penetration of 60 cm has been registered (Hayes et al., 1993).

In the case of the Prestige, and despite the rapid removal of the oil, high concentrations of oil buried in the sediment of the intertidal areas of the affected beaches were found at much greater depths than many examples referred to in the bibliography. This suggests the existence of a phenomenon of burial which goes further than the passive penetration of oil due to gravity which is what has been considered until now. The existence of this subsurface or "deep" contamination has a direct repercussion on the present cleaning methods and on the recovery of beaches. Different authors established that oil on sediments has a slow rate of degradation (Blumer et al., 1973; Keizer et al., 1978; Mayo et al., 1978; Teal et al., 1992; Hayes et al., 1993; Burns et al., 1994). This is mainly related to the reduction of abrasion and oil dispersal, as well as evaporation and oxygen and nutrients available for biodegradation (Johnston, 1970; Owens, 1978; Venosa and Zhu, 2003). This, along with the difficulty of its elimination using the normal remedial techniques for beaches causes the oil to be more persistent.

Hence, in order to improve cleaning methods, a better knowledge is required of the extensive contamination of the intertidal areas affected by an oil spill, determining the implied factors in the burial and analysing the processes of oil degradation in these conditions. Thus, this work which was carried out fourteen months after the Prestige disaster tackles these aspects in one of the most affected areas of the North-western coast of Spain.

2. Area studied

The 'Costa da Morte' (Galicia, N.W. Spain) was one of the coastal stretches most affected by the successive oil spills caused by the sunken oil tanker. It is situated between the Corcubión Ría to its south, and the Camariñas Ría to its north (Fig. 1). The studied area focuses on the intertidal section of the Nemiña and O Rostro Beaches found in the inner area of the Lires Ría. Nemiña Beach which is 1500 m long and 25 m wide (Fig. 2a), is situated to the north between the cape of 'La Vela' and the cape of 'Barra'. It features three distinguished zones: the northern sector located among rocky outcrops and confined to its rear by a wall and a parking lot; the central zone with an area of dunes limiting the supratidal section; and the southern sector conditioned by the mouth of the Castro River. O Rostro is to the south of the ría. It is 2000 m long and 50 m wide (Fig. 2b). This beach has three slow flowing river mouths to the north and to the south and central zone of the beach, crossing the ample dune field which confines the back part of the beach. The Lires ría is an area which is not very developed or industrialised, and was one of the areas most affected by the Prestige oil spill.

Using the information given by the Spanish Grid of Measure and Record of Waves (REMRO) and the Ministry of Public Engineering and Public Transport (MOPT) along with the tidal data provided by the Spanish Grid of Gauges (REDMAR) and the models of the generation of swell waves from the Ports of State, corresponding to the WANA point 1042072 (lat. 430,000, long. – 9.5) located of the Fisterra Coast, we were able to identify the wave climate of the studied area by way of a wave rose

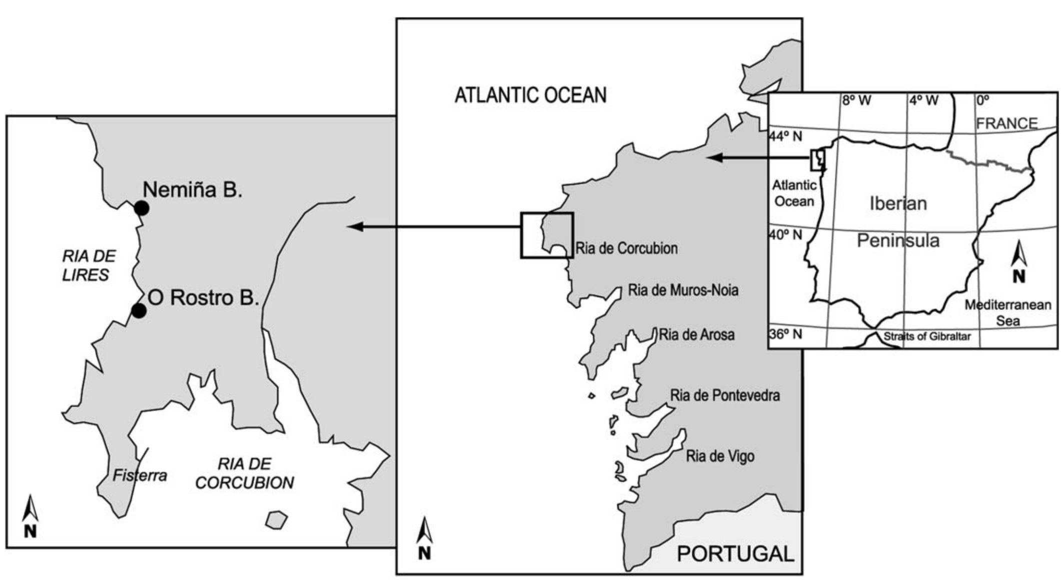

Fig. 1. Location of the area studied on the Galician coast and the position of the two beaches studied.

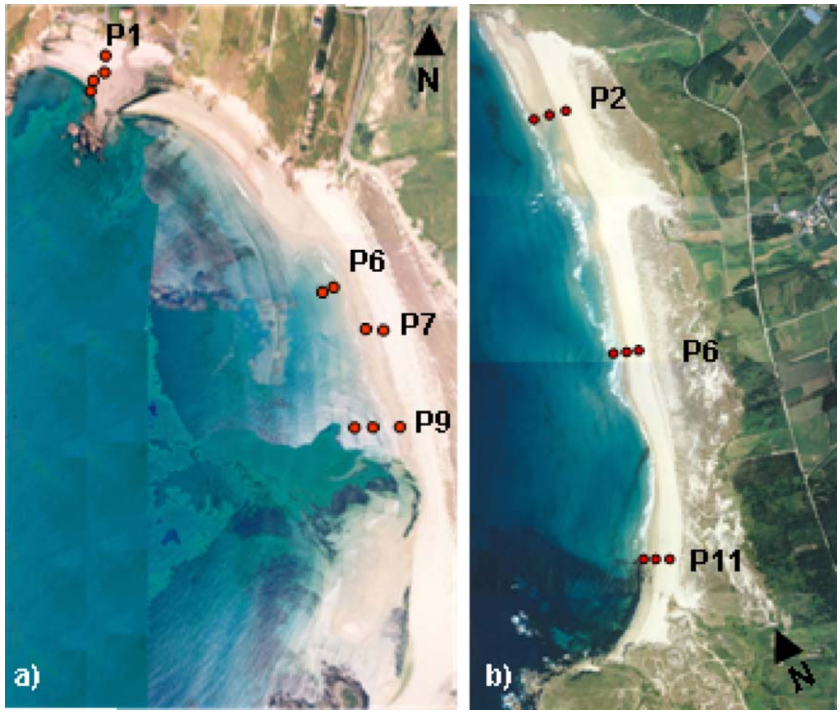

Fig. 2. Photograph of the two beaches studied: (a) Nemiña Beach and (b) O Rostro Beach. Position of the cores extracted from each beach.

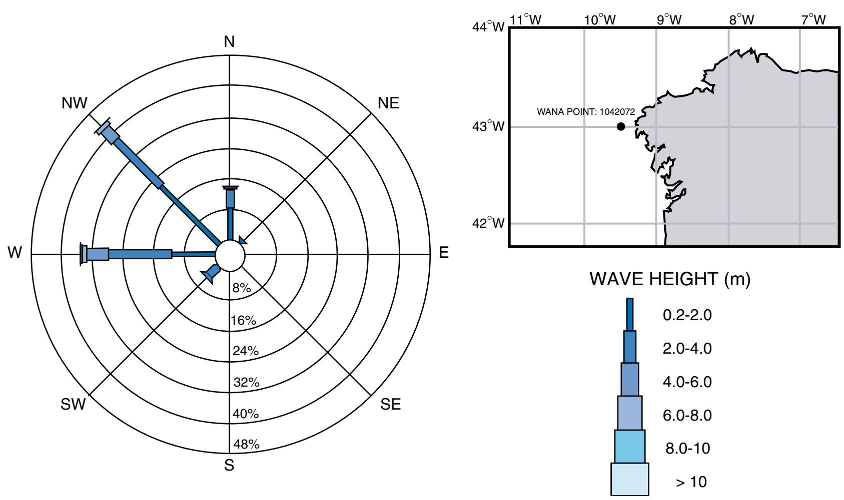

Fig. 3. Characterisation of the waves at deep water in the studied area by means of a wave rose. The data was obtained from propagation wave model given by public body Ports of the State, using the WANA 1042072 point situated off the coast of Fisterra as reference.

(Fig. 3). The Galician Atlantic Coast is generally exposed to energetic swell waves from NW to SW. The most frequent direction (40–50%) is from the NW and is known to experience waves higher than 6 m. The following direction is the swell waves from the W – between 30% and 35%, with waves which can also be higher than 6 m. Finally, the swell waves from the SW tend to occur less frequently (<10%), and are normally associated with stormy conditions with waves higher than 5 m. This coast is in the range of macro tidal beaches (Davies, 1964) based on the spring tidal range (over 4.15 m).

3. Methodology

The fieldwork was carried out on the 22nd and 23rd of January 2004, approximately fourteen months after the accident. It coincided with spring tides. The strategy was to extract cores from three cross sections of the beach: the northern, central and southern zones of each beach. Three cores were taken from each one of these sections perpendicular to the coastline: from the low intertidal zone (B), from the mid intertidal zone (IN) and from the upper intertidal zone near the high tide level (PL). A total of twenty cores were extracted from the two beaches studied. Eleven from Nemiña Beach and nine from O Rostro Beach.

The split half of each core was sampled at 10 cm intervals. The remainder of the sediment was saved for textural and geochemical analysis. Grain size was measured by dry sieving in all cores of the two beaches. Two cores of each beach were selected for geochemical analysis. Cores from Nemiña Beach were selected: NEM B 1, corresponding to the low intertidal zone, from the core north of the beach, and NEM IN 7, situated in the central stretch of the mid intertidal zone, where a large accumulation of oil was found at depth (Fig. 2). In the case of O Rostro, the cores analysed were: RO B 11 and RO IN 11, both found in the profile situated to the south of the beach, the area most affected by the oil spill, in the low and mid intertidal sections respectively. Elemental analysis was performed by X-ray fluorescence (XRF) to determine trace and major elements. Total organic carbon (TOC) and $CaCO_3$ content were estimated by LECO. The mineralogy of beach sediment was characterised by XRD. Selected samples were also examined by scanning electron microscopy (SEM).

The hydrocarbon concentration analysis was performed in four selected samples belonging to the core NEM B 1 from Nemiña Beach, taken from depths of 10, 30, 150 and 170 cm. The first two samples were found in the area of sand seemingly clean and the last two samples from the strip of grey sand. From O Rostro Beach, two complete cores were analysed: RO IN 2, from the north zone, less affected by the oil spill and RO B 11 from the area where large quantities of oil had reached. In the laboratory, about 5 g of dry sediment samples were extracted with hexane/acetone (1:1) in ASE equipment. Extracts were fractioned in a florisil column. Aliphatic hydrocarbons were determined by gas chromatography–flame ionisation detector (GC–FID) and the PAHs were analysed by gas chromatography mass selective detector (GC–MS).

4. Results

4.1. Granulometric characteristics

Nemiña Beach is composed of medium sand, with a mean grain size of between 0.33 and 0.5 mm. The surface distribution of sediment shows a longitudinal decrease in grain size, from the central zone (0.43 mm) to the northern extreme (0.33 mm) and south of the beach (0.38 mm). However, in the transverse direction following a profile of the beach, significant changes in grain size were not found. Vertically, the cores analysed presented a uniform mean grain size up to a depth of approximately 1 m, and from this point, a larger variability of this parameter is produced (Fig. 4a). The sorting of these samples varied from moderately well selected (MWS) to moderately selected (MS), with the coarser mean sized grains being the worsening of the sorting. In the majority of the samples, the skewness take on negative values ($-0.1/-0.3$) defining the deviation of the granulometric distribution towards the coarse fraction. On O Rostro Beach, the mean sand size is slightly coarser (Fig. 4b), entering in the medium-coarse sand fraction (0.38 mm–0.75 mm) and it presents a large variability both vertically and superficially. The surface sediment diminishes in size in a longitudinal direction from the central section (0.59 mm) towards the beach extremes (N, 0.41 mm; S, 0.46 mm). A variation in the mean grain size in the transverse section can also be appreciated, which diminishes from the subtidal area towards the high tidal zone. At depth, the analysed cores show a very variable grain size. With regards to sorting, it is situated on the MWS rank, apart from some very localised levels where the sorting is worse, coinciding with an increase of the mean grain size. The skewness of the samples oscillates between $-0.1/+0.1$ determining a normal distribution of sizes.

4.2. Geochemical analysis

On Nemiña Beach, the analysed samples contained more than 30% calcium carbonate. There is a difference established between the core situated in the low intertidal zone, with average values at depth which oscillate at around 45%, and the core found in the mid intertidal zone, with variations at depth of an average value of 55% (Fig. 4c). On O Rostro Beach, the calcium carbonate content is higher than 40% in all the samples (Fig. 4d). In both cores, the maximum values appear on the surface (up to 65%), diminish in the first 40 cm and, from this depth oscillate around 52%. On both beaches, the calcium carbonate content is high, determining the mineralogical composition of the sediment, which is composed of approximately 50% bioclastic grains and 50% siliciclastic grains. The bioclastic fraction is associated to the fragmentation of marine organism shells, whilst the siliciclastic fraction is mainly composed of quartz, potasic feldspar and micas. The microscopic observation of both fractions permitted the definition of the sediment texture where the bioclastic grains were characterised by their flattened form and its high angulosity, and the siliciclastic grains were characterised by a very rounded form.

During the field work, two main morphologies of the surface contamination on the beaches were identified: as particle oil of different size from some millimetres to various centimetres (Fig. 5a); and as iridescences on the surface of the sediment, due to the oil dissolved in the water (Fig. 5b). The observation and the processing of the extracted cores permitted the existence of oil at variable depths to be establish, reaching a depth of 2.38 m, corresponding to the maximum length of the extracted core. The same forms of oil appearence were recognised in depth, as the ones observed on the surface, particles of different size (Fig. 5c) and oil dissolved in the water (Fig. 5d). Furthermore, a new morphology was identified where the oil appeared impregnating the surface of the grains of sediment, giving it a greyish colouring characteristic at certain levels of the cores of a variable thickness (Fig. 5e and f).

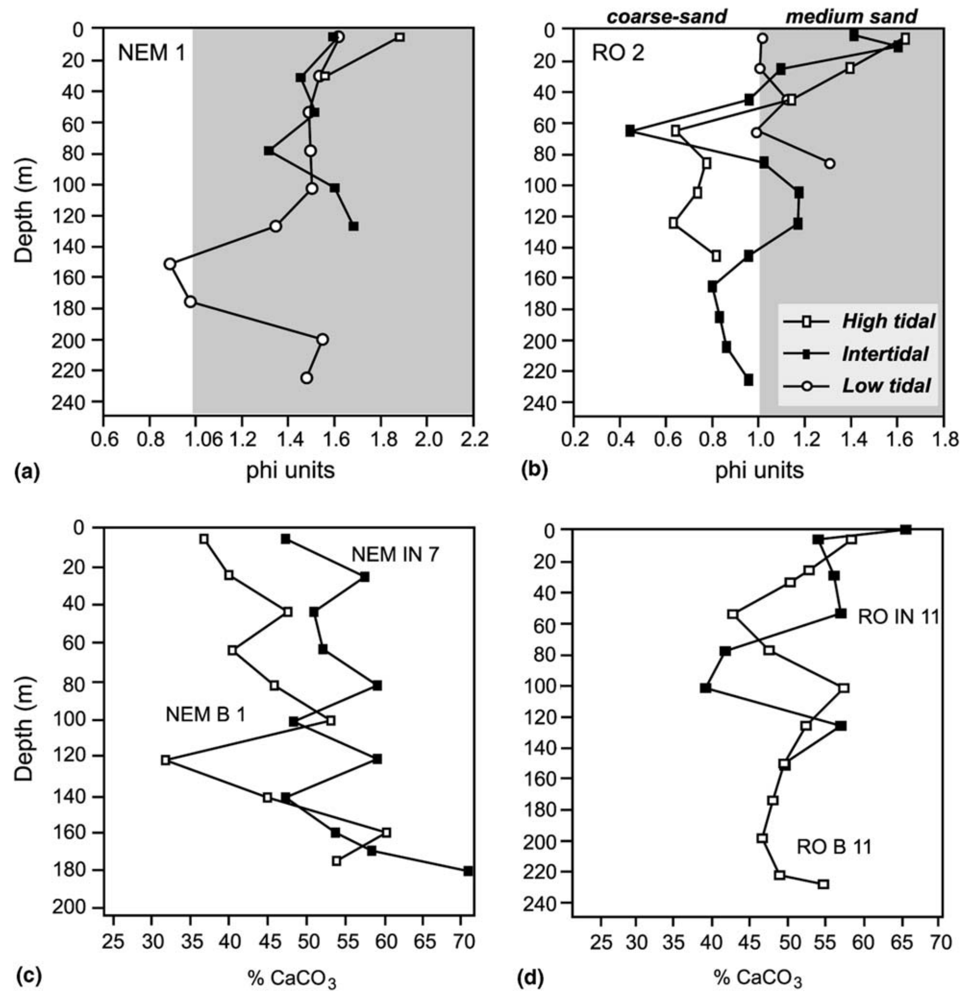

Fig. 4. Sedimentological characteristics of the studied beaches: (a) mean grain size, the results of the cores extracted from the profile situated in the northern sector of each beach are presented and (b) calcium carbonate content, the two cores per beach on which detailed analyses were carried out are presented.

These grey sands, present mainly on Nemiña Beach were examined by means of scanning electron microscopy. The studied samples belonged to the NEM IN 7 core, one of them taken at a depth of 20–30 cm, inside the area composed of seemingly clean sands, and the other sample was taken from the base of the core (183 cm), inside the grey sands layer. This way, the existence of oil coating on the sand grains was verified, which gave them an observed intense greyish tone (Fig. 6). The coating is discontinuous with a thickness of the order of microns and of variable extension. The analysis permitted the confirmation that the oil did not alter the structure of the sediment grains, but they simply adhered to them (Fig. 6b and d). On attacking these samples with hydrogen peroxide, the disappearance of the coating was verified, leaving the sediment grains with the characteristic golden tone. Some works (Delvigne, 2002) have analysed the relationship between the physical appearance of the oil and the grain size, among other parameters, concluding that differences do not exist in relation to the sediment. However, the examination by means of SEM of the coatings on the sediment grains showed a greater incidence on the bioclastic fraction, while on the surface of the siliciclastic grains the presence of oil was practically null.

The described morphologies of the oil determined a discontinuous vertical distribution. However, the detailed analysis has allowed the continuous presence of oil along the core in emulsion form to be established. This way, concentrations of vanadium, V, (2.9–9.1 ppm), nickel, Ni, (1–12 ppm) and sulphur, S, (0.3–1.2%) were detected, which were higher than the typical values of these coasts (Rubio et al., 2000; Villares et al., 2003), where the V and the S are practically not detectable and the maximum values of Ni (48 ppm) reaches zones very close to highly industrialised city centres. In the case of V, Nemiña Beach presented higher concentrations varying between 4 and 9.1 ppm; contrasting to the values of O Rostro which varied between 2.9 and 5.6 ppm (Fig. 7a). Nemiña Beach, also, presented higher levels of Ni, being more significant in the core located in the central area of the beach. This core (NEM IN 7) practically triples the concentration of Ni (6 ppm), present in the other three cores analysed, with 2.85 ppm

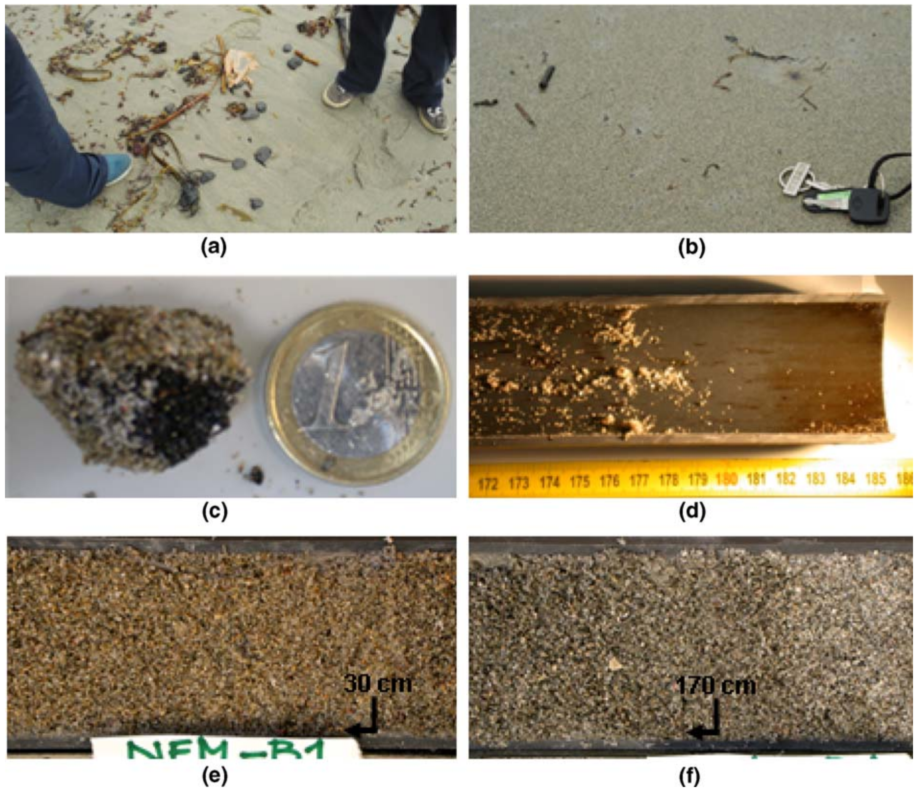

Fig. 5. Surface contamination on the beaches studied: (a) tar-ball of oil several centimetres in diameter, (b) iridescence due to the oil dissolved in water. Contamination in the sediment (c) tar-ball found at a depth of 20 cm in the RO B 11 core extracted, (d) stained testifier due to oil in emulsion, (e) seemingly clean sand (golden) in the upper part of the NEM B 1 core and (f) grey sand in the lower part (from 130 cm) of this same core.

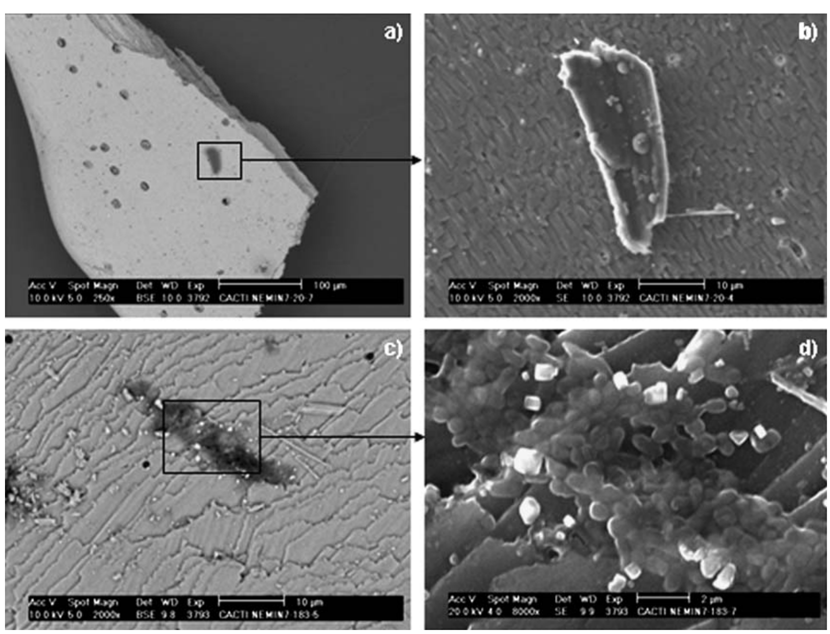

Fig. 6. (a) General view of a bioclastic grain with an oil stain on BSE, (b) detail of this stain on SEM, where the relief of the oil adhered to the grain can be appreciated, (c) another oil stain on a biocalstic grain, (d) detailed view of the stain on SEM, where the granular aspect of the oil and small salt crystals (NaCl) adhered to the oil can be seen.

in the core from this beach located in the northern zone, and in the cores from O Rostro Beach with values close to 1.81 ppm (Fig. 7b). This elevated value of Ni present in Nemiña Beach is partially related to the mineralogy of the sediment which in the past was exploited as ore of this element. This element presents maximum values higher

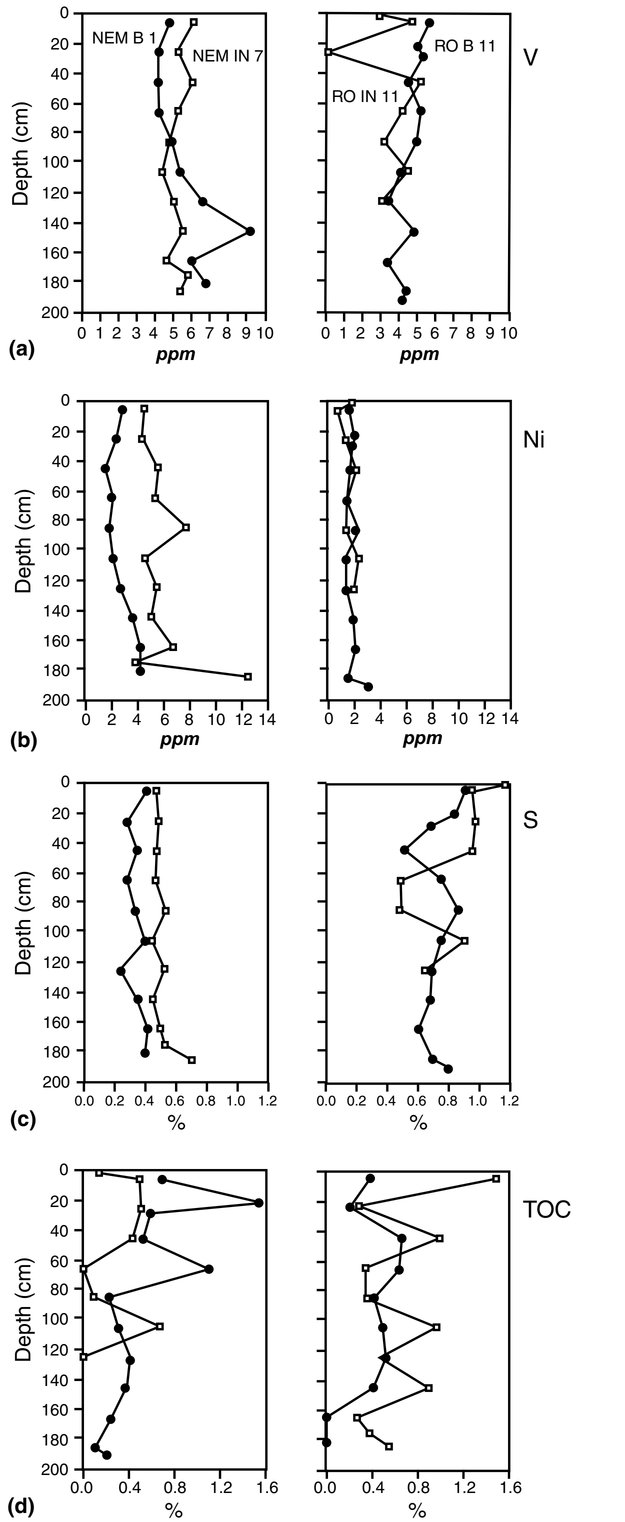

Fig. 7. Concentration profiles of: (a) vanadium, (b) nickel, (c) sulphur, and (d) TOC for two cores representative of Nemiña (NEM IN 7) and O Rostro Beach (RO B 11).

than 1000 ppm in different areas of the drainage basin which flows into the coastal zone near this beach. However, analyses carried out for the determination of the content of V and Ni (not presented in this work) indicated that these elements appear to be bound to the organic fraction, relating their origin to the presence of the Prestige oil. On Nemiña Beach, differences in the concentration of S among the studied cores are present. Whereas the core located in the north zone presents an average concentration of 0.35%, the core located in the central zone reaches a value of 0.51%. On O Rostro Beach, these values are practically duplicated, reaching an average value of 0.77% (Fig. 7c). An important characteristic of the presence of these three elements is that its concentration was maintained approximately constant through the cores.

In intertidal beach environments as have been studied in this work, the TOC under the top centimetres of sediment is practically null. However, average concentrations have been detected on Nemiña Beach of 0.63% for the core situated in the central zone of the beach and of 0.37% for the core located to the north. On O Rostro Beach values of 0.3% and 0.53% for the cores located in the mid and low intertidal zones respectively were detected. These concentrations of TOC which are relatively high in the analysed cores suppose anomalous values in beach environment (Fig. 7d).

Table 1
Mean concentrations of aliphatic and PAHs hydrocarbons in different sediment samples

Sample depth in core (cm)	Aliphatic hydrocarbons (μg/g)	PAHs (μg/g)
Nemiña Beach		
NEM B 1		
10	2.46	24.12
30	2.81	46.20
150	2.79	24.23
170	2.7	26.87
O Rostro Beach		
RO B 11		
10	9.8	229.01
30	13.9	569.63
50	7.6	171.57
70	3.2	66.74
90		
110	6.0	82.93
130	6.2	227.73
150	7.1	113.93
170	3.9	105.66
190	5.7	110.76
RO IN 2		
0	3.1	62.60
6	2.9	54.59
16	2.1	29.83
40	2.7	36.55
60	2.2	34.97
80	1.8	33.08
100	2.8	50.12
120	2.77	55.35
140	1.07	44.94
160	1.19	41.20
180	1.21	42.13
200	1.38	21.72
220	1.11	23.01

On Nemiña Beach, the results of the hydrocarbons analysis did not show significant differences of concentration of aliphatic hydrocarbons among the different samples analysed. In general, the concentrations of aliphatic hydrocarbons were relatively low, with an average value of 2.7 μg/g (Table 1). Furthermore, a homogeneous distribution of the hydrocarbons of even or odd number of carbon atoms was observed, the reason for which it can be considered that the origin of these compounds is petrogenic. On detecting neither pristane nor phytane, other indicators of origin could not be determined. As for the concentration of policyclic aromatic hydrocarbons (PAHs), it too was relatively low, presenting a maximum value (46.20 μg/g) in the sample found at a depth of 30 cm.

On O Rostro Beach, despite the relatively low concentrations of aliphatic hydrocarbons, the results showed significant differences between the two cores analysed, with average values of 2.1 μg/g for the northern core and of 7.04 μg/g for the southern core (Table 1). All the samples presented a similar profile, with the maximum concentration in the C22. These samples also presented a homogeneous distribution of the aliphatic hydrocarbons which supported their petrogenic origin. As for the PAHs, the difference of concentration between both samples is more significant, with an average value of the northern core of 40.78 μg/g, while the southern core reached an average value of 186.44 μg/g, with a significant maximum at a depth of 30 cm of 569.63 μg/g. The profiles of the samples were similar, phenanthrene being the major compound, with the exception of those which present a larger concentration of PAHs, in which other compounds also appear.

The relation phenanthrene/anthracene with a value superior to 10, together with a value less than 1 of the relation fluoranthene/pyrene, characterises a contamination due to petroleum. Also, the low concentration of naphthalene present in the samples reflects the rapid degradation of this compound into the environment opposite other compounds such as phenanthrene and anthracene. In this way, the naphthalene/(phenanthrene + anthracene) will decrease with time, being a good indicator of degradation of the oil. In some samples, methylnaphthalene and other methyl PAHs, which are more resistant to degradation, were detected.

4.3. Morphodynamics characterisation

From the models of wave generation from the Ports of State, corresponding to the point WANA 1042072, we obtained the wave parameters (wave height, period and direction) in deep waters (depths where the waves do not interact with the sea bed), from the outset of the Prestige oil tanker accident until the moment of the field work (Fig. 8). During this period, four important storms with wave heights of more than 5 m and with duration of more than three consecutive days have been identified (Table 2). The first of these took place during the days following the catastrophe, between the 19th and 22nd of November 2002. At this time, the 'Costa da Morte' was undergoing

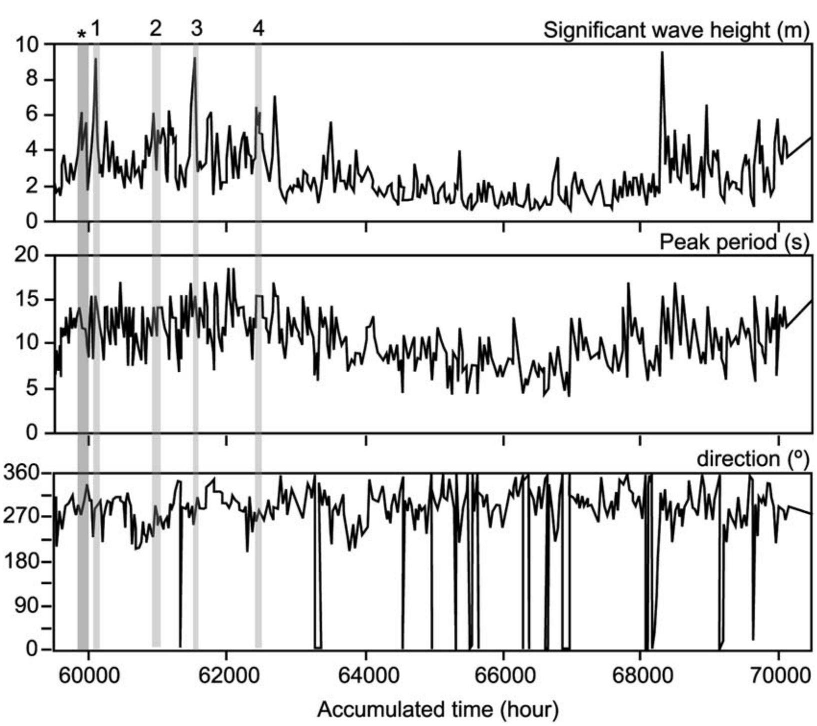

Fig. 8. Time series of significant wave height, peak period and direction of wave incidence in deep water in the area studied, obtained for the WANA 1042072 point, from the accident of the Prestige oil tanker (*) to the field work. Four storms registering wave heights of above five meters and which lasted longer than three days are identified (1, 2, 3, 4, see Table 2 for specific characteristics).

Table 2
The main characteristics of the four identified storm events since the Prestige disaster

Storm date (d/m/y)	Maximum wave height (m)	Wave period (s)	Mean direction (°)	Duration (days)
(1) 19–22/November/02	9.34	15.5	282	4
(2) 27/December/02 2/January/03	6.14	14	266	7
(3) 22–24/January/ 03	9.27	15.5	294	3
(4) 27/February/03 3/March/03	6.43	15.5	290	5

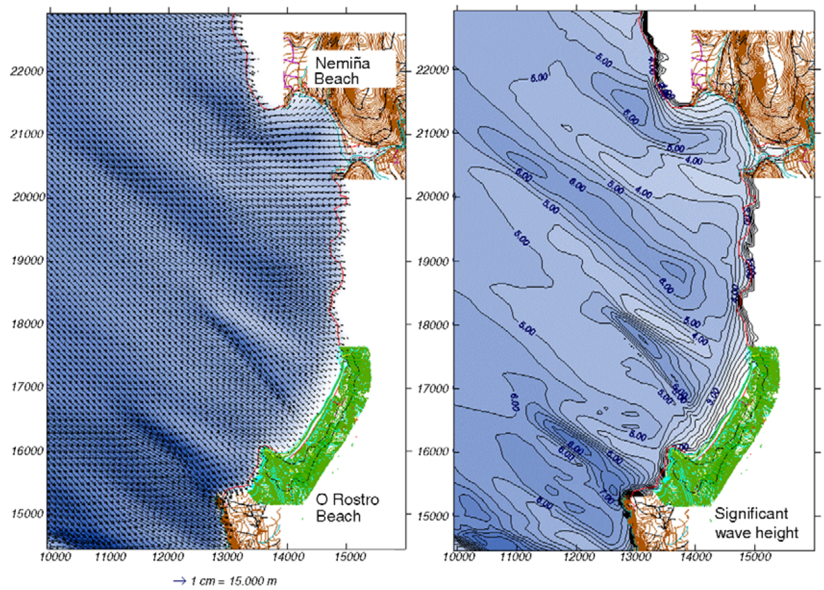

Fig. 9. Wave propagation from deep water to the interior of Lires ría for initial conditions of: $H = 6$ m, $T = 16$ s, dir = NW. In this simulation the different degree of the exposition of Nemiña and O Rostro Beaches to the most frequent waves was observed.

one of the most intense storms, with a maximum wave height of 9.34 m and a period of 15.5 s, coming from the WNW (282°). The other three storms were registered in the following months, during the arrival of successive oil spills from the zone of the sunken tanker, and they presented a variation in the direction of the average wave incidence of between 266° (WSW) and 294° (NW). From March 2003, there were no storms conditions ($H > 5$ m), during a time interval of more than a day, for which reason the extreme conditions registered after the catastrophe have not been repeated.

In spite of the general wave characteristics in the area studied, the orientation of Nemiña and O Rostro Beaches determines its degree of exposure to incident waves (Fig. 9). In turn, the energy level that reaches the beach conditions its morphodynamic behaviour and the annual volume of mobilised sediment. In general terms, Nemiña Beach, with a NW–SE orientation, is open to the SW. Therefore, this beach is protected from the most frequent waves which affect this area (arriving from the NW and W). However, it is exposed to waves coming from the SW; this assisted that this beach was one of the most affected by the arrival of oil from the Prestige, during the storm that took place between December 2002 and January 2003, where the dominant wave direction shifted towards the WSW. O Rostro Beach has a NE–SW orientation, being exposed to the most frequent waves and protected from the SW waves by the cape of O Rostro. Thus, despite the geographical proximity of the two beaches studied, its orientation regarding the incident waves establishes substantial differences both in the degree of energy, and in the frequency of the waves action, associated to their frequency of presentation, with a direct consequence on the behaviour and the morphodynamic evolution of each beach.

5. Discussion

Most works published on contamination produced by oil spills on beaches, such as those which approach remediation experiments in the laboratory and field (Owens, 1978; Miller and Mudge, 1997; Rowland et al., 2000; Pereira and Mudge, 2004), as well as real cases (Hayes et al., 1993; Teal et al., 1978; Kingston et al., 2003; Lee et al., 2003; Sergy et al., 2003), limited the analysis to the first centimetres of the sediment, assuming that the oil is incapable of penetrating deeper. The working hypothesis of these studies is that the burial of the oil occurs passively, depending on factors such as the viscosity of the oil or the porosity of the sediment and being limited by the position of the groundwater.

In Nemiña and O Rostro Beaches oil has been detected to depths of up to 2.38 m, its existence being probable at greater depths. This supposes that the oil has extended deeper than the groundwater, which some authors (Owens, 1978; Miller and Mudge, 1997) define as the depth limit of the burial of oil by passive mechanisms. Keeping in mind the high viscosity of the oil from the Prestige, and therefore its low capacity for penetration into the sediment (CSIC report, 2002), the existence of other burial and oil-sediment mixture mechanisms not considered until now are evident. In relation to this, these works done on the beaches obviate one of the fundamental characteristics of this sedimentary environments: the intense sediment mobilization associated to the variations in the wave conditions. Only Owens et al. (2002) has suggested that the seasonal pattern of sand migration has some significance in the tar-balls concentration in a beach, although these authors solely attended to their surficial distribution. The results of the present work have allowed the development of a conceptual model of the burial and evolution of the oil from its arrival to the coast, which integrates this new factor (Fig. 10).

The arrival of the oil from the Prestige coincided with one of the biggest storms of that period, and in the subsequent months, with the succession of up to four storms with similar conditions of H and T, altering the direction from NW to WSW. Under these storm conditions, the upper part of the beach profile (the high intertidal zone) tends to erode, losing sediment which is transported to the subtidal zone. This process generates a decrease in the average slope of the profile. Initially, when the oil reached the coast it was deposited in extensive layers which accumulated in the intertidal areas of the eroded beaches. A large part of this oil was removed by means of traditional cleaning techniques. The oil that was not eliminated was subjected to the action of the wave breaking which occurs in this narrow coastal strip (Fig. 10a). The breaking phenomenon generates very energetic, turbulent movements capable of stirring the sediment at the bottom in a very efficient way. This mechanism was responsible for the initial fragmentation of the large layers of oil present on the beaches, as pointed out Santas and Santas (2000), and the active mixing between the oil and the sediment (Fig. 10b). This way, tar-balls with sediment of several centimetres in diameter were generated, which spread in the intertidal area of the beaches. In the calm conditions after the storm, the wave conditions are less energetic, favouring the transport of sediment from the lower part (subtidal) towards the higher part (intertidal) of the beach profile. The consequence of this was the burial and the dispersion of the tar-balls in the sediment, which could be observed during the field work.

From March 2003, the wave conditions were more favourable. The sediment continued to shift towards the intertidal and supratidal areas of the beach, carrying the oil deposited in the deeper zones and increasing the burial depth in the beach to the values registered during the sampling. In this situation, oil actually appeared below the groundwater level of the beach, contrary to what has been seen previously (Owens, 1978; Miller and Mudge, 1997). This typical cyclical behaviour of beaches has been described in detail by different authors such as Wright and Short (1984), Masselink and Short (1993) or Bernabeu et al. (2003).

However, the morphodynamic behaviour of the beaches not only affects the phenomenon of burial and mixing of oil, but will also determine the subsequent evolution of the oil. This way, during the burial, the rate of the oil biodegradation becomes slower. In contrast to this decrease in microbial activity, the tar-balls embedded in the sediment are subject to the pressure exercised by the sedimentary column, intensifying the oil-sediment mixture and generating, as a last resort, deformation and a secondary process of the fragmentation of the tar-balls (Fig. 10c). From this point, the evolution and degradation of the oil will depend directly on the morphodynamic variability of the beach, as has been observed in the two beaches studied.

O Rostro Beach, due to its orientation open to the most frequent waves, can be considered an exposed beach, subject to intense and variable waves. This condition is reflected in its sedimentological characteristics (coarse grain size, a normal granulometric distribution and MWS) typical of high energy environments. The action of the waves produces the frequent shifting of the sediment, which is why the oil remains buried for short periods of time. The dynamics of the beach favours the burial-exhumation cycle of the oil and its transport, together with the sediment, from the subtidal area to the intertidal area and vice versa. During this transport, the interaction between the oil and the sediment intensifies abrasion, where the tar-balls diminish in size progressively, until they form particles of about mean grain size (Fig. 10d). On reaching this point, sedimentation is produced on the beach front, a phenomenon of selective transport acts. The millimetric oil particles tend to accumulate principally on the layers of higher concentration of bioclastic grains, as was observed during the sampling.

Nemiña Beach is protected from the most frequent waves, which is reflected in its poorly sorted sediment and its asymmetrical granulometric distribution. In this case, the mobilization of the sediment is less frequent and the oil remains embedded for longer. Under these conditions, abrasion and the dispersion of the oil associated with the direct wave and tide action are reduced (Johnston, 1970; Owens, 1978). However, the buried oil residues are subject to a hydrodynamic phenomenon of a lesser time and space scale, the oscillation of the groundwater level. According to Masselink and Turner (2000), this is determined by the character of the beach sediment (grain size, sorting and porosity) and by the hydrodynamic parameters, fundamentally the waves, tide and rainfall. As a consequence of this variation in the position of the groundwater level, a flow of water is generated characterised by the filtration of sea water in the direction towards land during high tide, and the exfiltration of fresh water in the direction of the sea during low tide, Fig. 10e. This flow

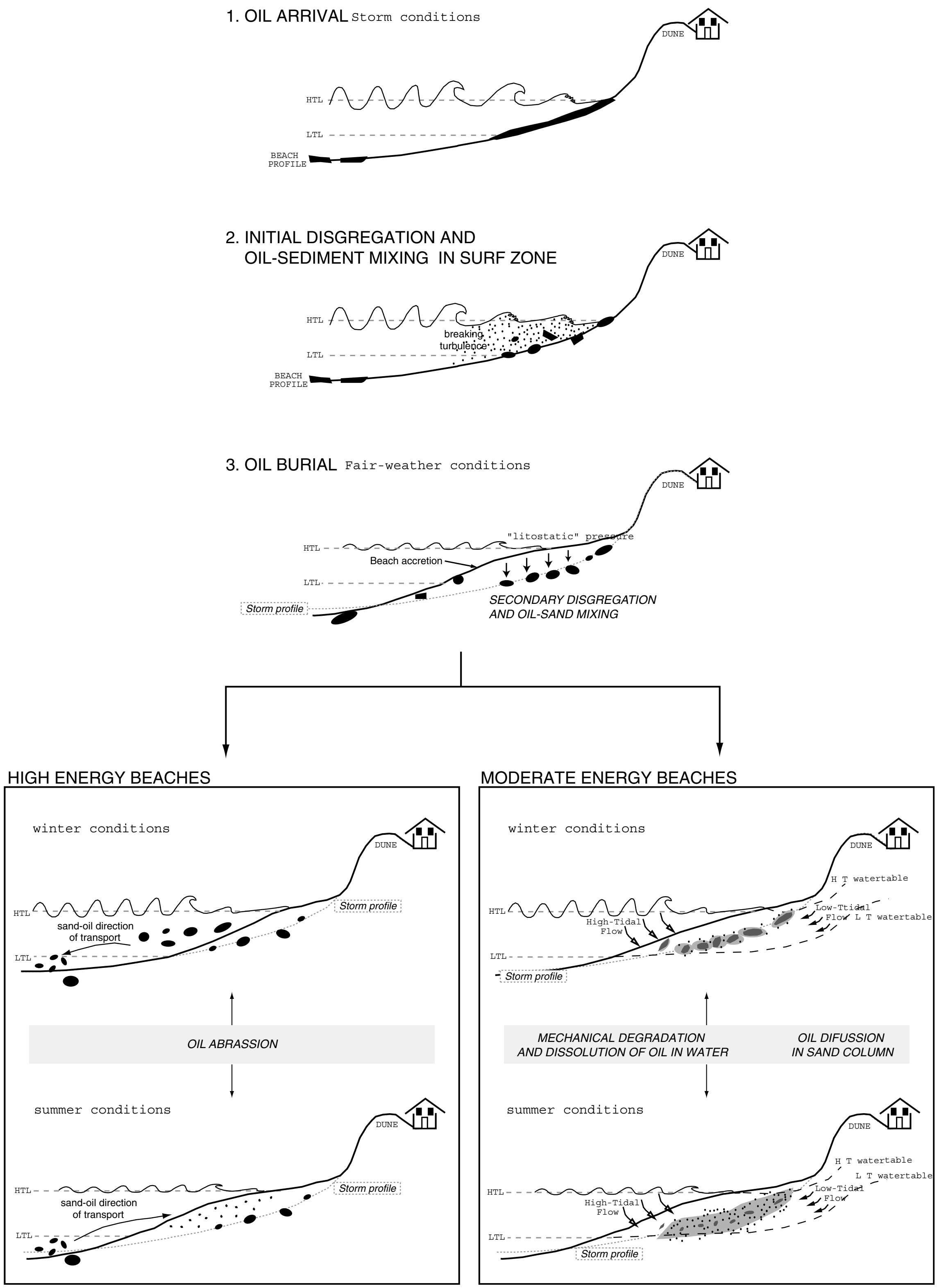

Fig. 10. Model of burial and subsequent evolution of the oil in the sediment of the intertidal zone of a beach.

exerts a double effect on the buried oil. On one hand, it produces small movements of the sediment grain, increasing friction. Keeping in mind the selective oil accumulation in the bioclastic levels, as was observed during the sampling, made up of flat and angular grains, this re-settling favours the disintegration of the embedded oil. As the oil fragments into smaller particles, the water flow permits its transport through the sedimentary column. On the other hand, this flow acts directly on the buried oil, favouring the dissolution of the hydrocarbons in the interstician water;

and pumping and diffusing the oil along the sedimentary column. The appearance of oil coatings on sediment grains forming layers, which in some cases reached more than a metre of thickness is presented as an indicator of this diffusion process in the sedimentary column. Also, the presence of levels of PAHs and aliphatic hydrocarbons, even at depths and in samples where the oil was not visible establishes that the distribution of oil in emulsion is uniform along the sedimentary column.

Despite the sedimentological similarity between Nemiña and O Rostro Beaches, the different morphologies of the buried oil present in each beach demonstrate the existence of distinguishing mechanisms. The different degree of wave exposure of each beach and its morphological response are presented as one of the most important. Ultimately, this group of processes reveal the existence of an important mechanical degradation of oil unidentified until now, which would jointly act with biodegradation and chemical degradation on the beach sediment, accelerating the natural disappearance of the contamination.

6. Conclusions

The morphodynamic behaviour of the beaches has been identified as a determinant factor in the burial of oil in the intertidal area. The different morphologies of appearance of oil on each one of the beaches show that the morphodynamic behaviour also has a direct influence on the evolution of the embedded oil, with the mechanical processes strengthening when the microbial activity slows down. Moreover, the morphology called oil coatings shows a larger incidence on bioclastic grains, for which reason, under certain conditions, the physical appearance of the oil is affected by the mineralogical composition of the sediment.

This information has allowed the development of a model of evolution of oil in the sedimentary column, which establishes the hydrodynamic processes implicated (fundamentally, waves and variation of the groundwater level) and the different ways of mechanical degradation of the oil. The morphodynamic behaviour of the beaches is presented as a determinant factor which should be incorporated into the existing models of clean-up and coastal recovery, in order to estimate the time of recovery of the sandy beaches and the effectiveness of the clearing methods in the most precise way.

However, within the proposed model, and from the existing data, it is not possible to determine the time scale of these processes, nor the influence that the possible contributions of oil from the continental shelf would have on this natural process of sediment regeneration, for which reason this model is put forward as a basis for subsequent researchs into this field.

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