Preliminary report on:

The coastal ecosystems 10 years after the 1991 Gulf War oil spill

by

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Abstract:
In 1991 the Gulf War lead to the largest oil spill in human history. Over 700 km of coastline from southern Kuwait to Abu Ali Island were smothered with oil and tar, erasing most of the local plant and animal communities. On the basis of the numerous results produced by the EU-NCWCD project until 1995, 10 years after the oil spill a thorough reassessment was carried out. The study was aiming at the processes of natural regeneration taking place at the different coastal ecosystem types occurring along the Saudi Arabian Gulf coast. The study demonstrated that, in contrary to previously published reports e.g. already 1993 by UNEP, several coastal areas even in 2001 still show significant oil impact and in some places no recovery at all. The salt marshes which occur at almost 50% of the coastline show the heaviest impact compared to the other ecosystem types after 10 years. Completely recovered are the rocky shores and mangroves. Sand beaches are on the best way to complete recovery. The main reason for the delayed recovery of the salt marshes is the absence of physical energy (wave action) and the mostly anaerobic milieu of the oiled substrates. The latter is mostly caused by cyanobacteria which forms impermeable mats. In other cases tar crusts are responsible. The availability of oxygen is the most important criteria for oil degradation. Where oil degrades it was obvious that benthic intertidal fauna such as crabs re-colonise the destroyed habitats long before the halophytes. The most important paths of regeneration are the tidal channels and the adjacent areas. Full recovery of the salt marshes will certainly need some more decades.

Objectives

- Analysis of intertidal soil samples in order to show the impact caused by the oil residues.
- Documentation of regeneration within different coastal ecosystems.
- Damage assessment 10 years after the oil spill.

Methods

Sediment samples were cored by an Eijkelkamp coring device. Standard grain size analysis war carried out at the Jubail Marine Wildlife Sanctuary centre. Carbonate content was determined by the Method after SCHEIBLER in the laboratory of the Ggeographical Institute in Regensburg, Germany. Groundwater chemistry was analysed by a Merck photo spectrometer in Jubail.
The oil print rapid assessment was developed during our field work in Jubail. This method is based on the fact that oil is floating on water. Multiple rinsing of 10 g sample with a defined volume of water (5 x 20 ml water) and collection of the extract (in a vessel with a capacity of exactly 100 ml so, that after filling, the water-oil surface is level with the vessel fringe), leads to a sufficient amount of oil floating on the water surface, which can be printed on a stable absorbent paper. The oil is absorbed by the paper as soon as it contacts the water-oil surface. In most cases the oil is absorbed completely by one paper print. More degraded oil constituents develop a strong hydrophobia. It can therefore not be separated from the sediment and will not show on the paper print. This is an important advantage to the quantitative hydrocarbon extraction with solutes, where well degraded oil residues are also extracted and might indicate a high degree of oil in the sediment.
Hydrocarbon analysis was carried out in Regensburg. Gas chromatography was not applied because of the aged samples (several weeks from collection until analysis in Germany). 10 g of the samples were extracted by standard Soxhlet extraction with dichloromethane.
Some air dry samples of laminated cyanobacteria mats were radiocarbon dated in order to determine the fraction of fossil carbon (originating from the oil).
Field studies were continuously carried out starting in October 2000 until May 2001.

Results

Mapping of the coastal ecosystems:

The coastline of the sanctuary covers 401 km (Barth et al. 1994). It consists of the following ecosystem types (basis for evaluation were helicopter flights 1993/1994 and ground truth cartography in the filed from 1994 – 2001):

190 km salt marshes (out of which 145 km show a width greater than 15 m and 45 km a width smaller than 15 m).
146 km Sandy shores (90 of which are low energie sand beaches and 56 km high energy shores)
45 km Sabkha (sabkha - mudflat transition with no vegetation)

14 km Rocky shores
6 km Mangroves

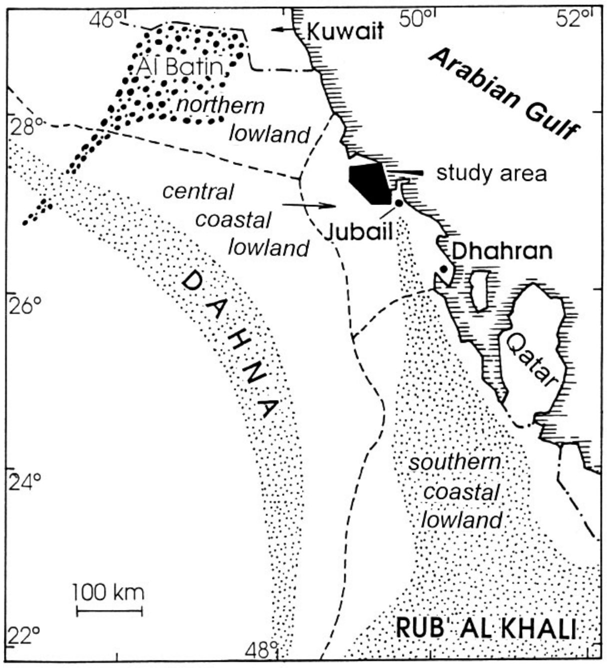

Fig. 1 Location of the study area.

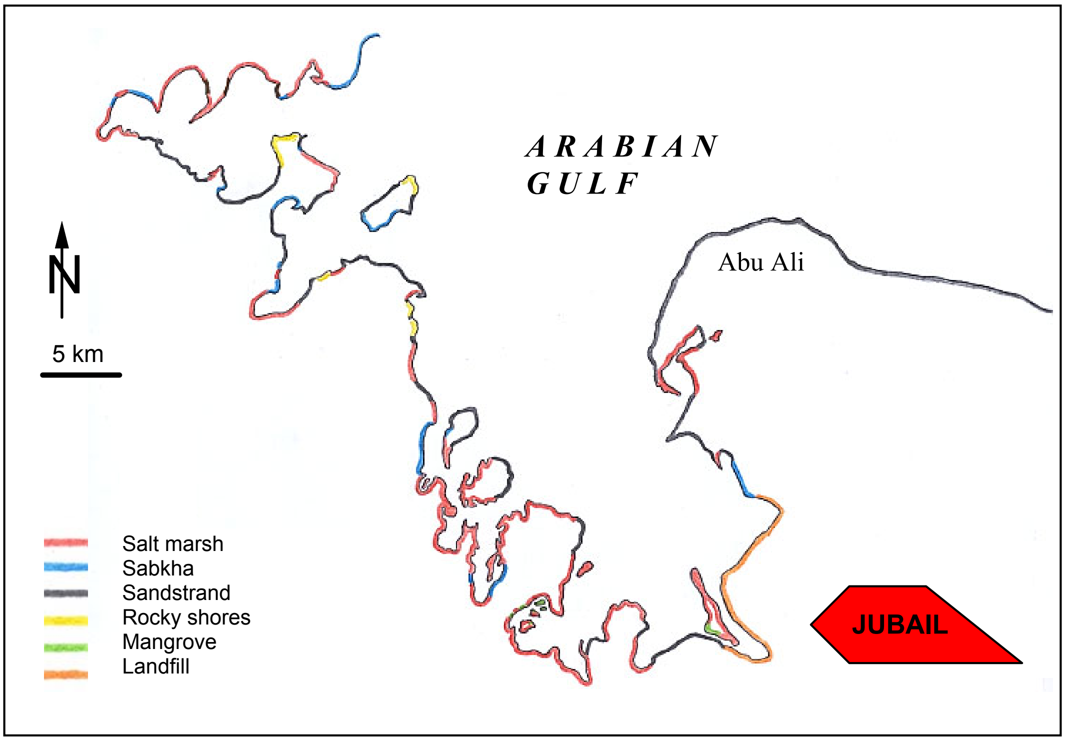

Fig. 2 Location of the different coastal ecosystem types within the study area.

Status of the different ecosystem types in spring 2001

Salt marshes: 90% - 95% of the salt marshes were oiled in 1991. Only 20% of these can be considered as fully recovered in 2001 whereas about 25% are still completely dead without any sign of regeneration.

Sandy shores: Most sand beaches are narrow (due to higher energies by wave action). They were all oiled in 1991. Around 80% of the sandy shores are recovered in 2001 although still oil residues may be found buried beneath new sand. But species composition is similar to non oiled control sites.

Rocky shores: All rocky shores were damaged by the oil in 1991. Physical wave action accelerated the oil degradation and regeneration of these ecosystems. Today 100% of these shores are recovered. Occasionally new oil patches may be found which drifted onshore, but they not related to the 1991 oil spill.

Coral reefs: The reefs were only slightly affected by the oil or not at all (Vogt 1996). The fish had recovered from the effects of the oil spill already in 1994 (Krupp & Almarri 1996).

Salt marshes

Salt marshes are the most abundant coastal ecosystem type along the Saudi Arabian Gulf coast. 190 km coastline covered by salt marshes make around 47% of the total coastline within the study area. Due to the low lying coast the intertidal zone is very extensive and can reach more than a kilometre in width (Krupp & Khushaim 1996). The average is estimated to be around 200 to 300 metres. Salt marshes grow on mudflats which form in areas where wave and current energies are low. Fine particles are therefore the main sediment fraction that settles in such an environment, which is often cut by meandering tidal channels through which the ebb tide drains. The salt marshes are composed of halophytic plants which are capable of withstanding inundation by seawater. Due to the extensive intertidal zone and the high tides in March 1991, salt marshes as the most prominent upper shore biota were most severely affected by the oil resulting from the Gulf war. The zone between the spring high water mark and the neap high water mark were covered by a continuous band of oil and tar with devastating effects to the fauna and flora of the ecosystems. Crab burrows enabled the oil to penetrate up to 60 cm into the fine grained usually impermeable sediments. All benthic fauna as well as most halophytes were destroyed after the oil settled along the shores (photo 1). The physical energy of the tides is not measurable. Only small amounts of fine sediments were occasionally deposited. In the places where that happened cyanobacteria rapidly colonised the flats. This was possible because cyanobacteria need undisturbed substrate to grow on. Former bioturbation by crabs and polychaetes prevented an extensive settlement of cyanobacteria. Now after complete destruction of the salt marsh biota and some deposition of new sediment the conditions for cyanobacterial growth were ideal. They form leathery mats which can grow up to a thickness of some centimetres (if the deposition characteristics of fine sediments is favourable). Such a layer of laminated cyanobacteria is impermeable and creates an anaerobic environment below the mats (photo 2). At such sites even 10 years after the oil spill liquid oil is still present in the upper sediments. The hydrocarbon concentrations are similar to the ones in 1991 showing values of up to 50 g/kg. Degradation of the oil has been very slow and no biota could be observed.

Photo 1 Oiled salt marsh 1993. All plants died after the oil impact.

Photo 2 Leathery cyanobacteria mats. Horizontal growth and area expansion cause the blisters.

Cyanobacteria and their role of hydrocarbon transport

The main growth season of laminated cyanobacteria (especially *Microcoleus sp.* and *Lyngba sp*.) is during the summer months. In the winter period high tides provide more sediments which settle on top of the cyanobacteria (about 1-3 mm). In spring the filamentous bacteria grows and covers the new sediments. This repeated process leads to one layer of sediment and cyanobacteria respectively each year. The older bacteria dies and remain in an anaerobic milieu. That is the reason why we found 700 years old cyanobacteria even 70 cm below sediments (Barth 2001). At one site cyanobacteria growing on the sediment one year after the oil spill was dated by the radiocarbon method and then the overlying layers. The first sample showed an age of 8800 years BP. The age of the following layers decreased significantly from 1070 BP, 800 BP and 630 BP. This means that in the first layer of bacteria (after the oil spill) about 75% of fossil organic carbon was incorporated. The fraction of fossil carbon decreases gradually and amounts in the 9th layer above the oil (9 years after the oil spill) 10%. Because of the gradual decrease the single impact from 1991 seems to be responsible for the fossil carbon. This implies that small amounts of hydrocarbon deposited in the 1991 oil layer are able to rise to the surface. Most probably because each new layer of cyanobacteria incorporates some of the carbon provided by the layer immediately below.

At other places where no new sediments are being settled cyanobacteria contribute to the bioremediation process. Desiccation of the mats leads to contraction, fracturing into pieces and thereby breaking up the tar crust. Wind and water then remove the dried mats together with part of the tar (photo 3). This process has been observed by Höpner et al. (1996). It continues in 2001. Our opinion is that this process indeed contributes to bioremediation but in most cases it is a slow process that needs a time span of one or two decades to completely break up a tar cover (provided that cyanobacteria grow there each year).

Other areas without cyanobacterial growth are still in a bad condition in 2001. Often hardened tar crusts are still present, preventing crabs and other organisms from bioturbating the substrat. Only in very few places new *Arthrocnemum macrostachyum* could be observed within tar encrusted substrate. This happens only at places were the hard crust is broken physically (by bioturbation).

Photo 3 Peeling of dried cyanobacterial mats after desiccation removing some of the tar from the underlying crust.

In areas where regeneration exceeds the prime stadium of single germinating plants within a wide area, tidal channels play a major role. Tidal channels are the guide lines for recolonisation by animal life. Fresh sea water and plenty of food provide an environment suitable for these organisms. From the tidal channel the adjacent sediments are bioturbated. This action increases the oxygen concentration within the sediment significantly, which accelerates the biodegradation of the oil. Then the crabs can expand into the areas of degraded oil and the process continues. The tar crust eventually will break which smoothes the way for resettlement by plants. Up to now this can be observed in areas 5 to 15 metres adjacent to tidal channels. This demonstrates that the recovery takes place but at a very slow pace. It is estimated that the complete recovery of such ecosystems will take many more decades.

Photo 4 Regeneration within salt marshes follows the tidal channels. Some new plants grow adjacent to these channels where bioturbation (mainly by crabs) loosened the compacted substrate.

The significance of oxygen regarding the biodegradation of oil has already been pointed out by Smith 1996. In order to proof the acceleration of natural recovery a test area covered by dense cyanobacterial mats was established. Perpendicular to a tidal channel at a stripe of three metres width and 50 metres length the mats were broken and the sediment loosened until a depth of 10-15 cm. This area should be visited again in March 2002 in order to check whether oil degradation took place, recolonisation by crabs and other organisms started and initial germination of plants is visible or not. It will also be of interest whether cyanobacteria regains the loosened substrate or not.

The following figure 3 shows a salt marsh profile with sediment cores, rapid assessment oil prints and photographs. Vegetation decreases already 50 metres before the oiled zone. At the 90 m mark some individuals of *Arthrocnemum macrostachyum* survived and show now, 10 years after the impact, new shoots (photo 5). Young plant individuals were not present at all. At the 105 m mark no more living plants are present. Some surviving plants finally died off in 1994. The sediment shows a deep brown colour in the first 5 cm caused by oil residues. These residues are degraded to an advanced level which does not prevent most animals from colonising such an environment. But still the amount of 1.5 crab burrows per square metre (average value) is extremely low and only very few living organisms could be observed. Although the total hydrocarbon concentration is relatively high (18.2 g/kg soil) the rapid assessment print shows no colour which demonstrates the advanced degradation of the hydrocarbons in this sample. Between the 120 and 135 m marks, the oiled sediment layer increases to 10 cm and the oil is less degraded. The sediment here is sticky and emitted a strong hydrogen sulphide odour. The total hydrocarbon concentration increases to 34 g/kg at the 150 m mark. The rapid assessment prints show a deep brown colour demonstrating a high content of less degraded oil. No living organisms were found in this area. The fine sediments below the oiled layer prevented a deeper penetration of the oil, although it penetrated deeper along former crab burrows (photo 6). At such places the oil is still liquid which collects at the water surface in section holes (photo 7). At the 260 m mark the surface is covered by a tar crust and poorly developed cyanobacterial mats. The stability of these crusts was very high with more than 4.5 kg/cm² around dead *Arthrocnemum* individuals and 3.5 kg/cm² in between the plants. Such hard surface crusts prevent any recolonisation by bioturbating animals. The first signs of activities of living organisms was observed from the 310 m mark on (new crab burrows, Polychaetae and Cerithids). The oil concentration in the sediment decreases gradually from the 260 m mark towards the sea (see lighter brown colour of rapid assessment print at 260 m mark) and at 310 metres the only signs of oil residues (well degraded) were observed in old crab burrows.

Photo 5 New shoots at damaged *Arthrocnemum. macrostachyum* in 2001.

Photo 6 Oiled crab burrow in 2001.

Photo 7 Liquid oil floating on the groundwater surface.

Sandy shores

Sand beaches are generally found at locations of higher physical wave energy (see figure 2). Waves drive oxygen into the sediment. In most cases just the physical energy of the waves was enough to rework the tar crusts, break and erode them within the first 2 - 4 years after the oil spill. Today the only remains of the oil spill are scattered oil pebbles at the beaches (photo 9). At some sites the oiled sediment was covered by a layer of fresh deposited sand. At such locations the oil layer is still present e.g. PTL 1 of the EU/NCWCD Project. Today high hydrocarbon concentrations of more than 20 g/kg are rarely found. In cases of higher concentrations again oxygen deficit below an impermeable tar crust was the obvious cause for the preservation of the oil.
Higher oxygen concentrations in most sandy sediments lead to a significant degradation of the oil in a manner that it does not prevent colonisation by animal life since more than 5 years (see also Jones et al. 1996). Therefore most sandy beaches can be considered as fully recovered after already 5 years.

Photo 8 Narrow tar band along a sandy beach. This band is being eroded by the physical energy of wave action (picture taken 1993).

Photo 9 Scattered oil pebbles are the only remains of the 1991 oil spill along most sand beaches in 2001.

Sabkha shores

The conditions at sabkha shores with a broad transition into the soft bottom tidal flats are very similar to the ones described for the salt marsh ecosystem, except the total absence of any vegetation due to extreme ground water salt concentrations.

Rocky shores

Some of the Tertiary limestones of the Hadruk- and Dam-formations remained at the coastline of the Sanctuary and form some stretches of rocky shores. The resulting cliffs are between 40 and 500 cm high. Wave action removed the oil cover already in 1992 (Jones et al. 1994). 1993 all key species were present again. Recovery of abundance was observed continually until 1995. Therefore all rocky shores were already completely recovered in 1995.

Mangroves

The Mangroves which are composed of only one mangrove tree *Avicennia marina* occur at very sheltered soft bottom sites, often in association with salt marshes. Tidal channels are widely distributed among the mangrove trees. After the oil spill around 50% of the trees were affected by the oil and around 30% died off (photo 10). Natural regeneration started 2 years after the impact. Using the tidal channels (see discussion at salt marshes) benthic organisms colonised the sediments adjacent to the channels and broke the surface tar crusts and allowed oxygen to penetrate into the sediments. Due to stronger water currents, a higher rate of inundation by sea water and a narrow network of tidal channels the process was much faster in this ecosystem type than at the salt marshes. The first mangrove seedlings germinated in the loosened substrate after two years (photo 11). 10 years after the oil spill most sites are aerobe and well bioturbated. Benthic organisms reached their original abundance and species diversity. The oil is well degraded or not detectable. Even at severely damaged sites 3-5 years after the impact new seedlings re-colonised the area (photo 12). Today the only signs of the impact are some remains of dead plants and very few tar residues. In these ecosystems the regeneration was much faster than previously (Böer 1994) estimated.

Photo 10 Bitumen sealed the soil surface limiting the penetration by oxygen water and benthic organisms.

Photo 11 New germinated seedlings among dead mangrove (picture taken by B. Böer 1993 in Böer 1996).

Photo 12 Young stands of 4 - 7 years old mangrove trees at a severely damaged location.

Recommendation for future research

The dominant role of oxygen in natural biodegradation of the oil became obvious. The oxygen requirements are hampered by cyanobacteria and tar crusts. At test sites these were loosened in March 2001 to allow a faster oil degradation. These test sites should be visited again in 2002 and 2003 in order to collect information on: oil degradation, resettlement of organisms and possible resettlement of cyanobacteria. In addition the possibility of oil migration caused by the partial removal of the crusts has to be considered.
Generally the direct role of cyanobacteria in hydrocarbon metabolism is not exactly known. I suggest some more baseline research regarding this subject. The extensive occurrence of cyanobacteria could be an economic factor if the produced biomass could be used in one way or the other (e.g. feedstuff supplements, medical applications, cosmetic applications etc.).
Finally in the geographical institute in Regensburg, Germany an electronic database will summarise all the important information collected in the 10 years of research in the Jubail Marine Wildlife Sanctuary. This information will be published in the internet in order to make it accessible to all interested people, ecologists, biologists, decision makers and urban developers. We are working on that as a next step, but it will not be finished until end 2002 or beginning of 2003.

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