Ecological, Radiological, and Toxicological Effects of Naval Bombardment on the Coral Reefs of Isla de Vieques, Puerto Rico

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Abstract

Between 1943 and 2003, land and sea areas on the eastern end of Isla de Vieques, Puerto Rico were used as a naval gunnery and bombing range. Viequean coral reefs are littered with leaking and unexploded ordnance (UXO). Radiological, biological, and chemical surveys were conducted to assay the health of these coral reefs.

Biotic surveys revealed a statistically significant inverse correlation between the density of military ordnance and several measures of coral reef health, including (a) the number of coral species ($p = 0.007$), (b) the number of coral colonies ($p = 0.02$), and (c) coral species diversity (H′) ($p = 0.0005$). Reefs with the highest concentrations of bombs and bomb fragments have the lowest health indices.

Water, sediment, and biotic samples revealed that: (a) every animal tested on the seaward reef of Vieques near unexploded ordnance contained at least one potentially toxic compound leaking from *in situ* ordnance [1,3,5-Trinitrobenzene; 1,3-Dinitrobenzene; 2,4,6-Trinitrotoluene; 2,4-Dinitrotoluene + 2,6-Dinitrotoluene; 4-Nitrotoluene; 2-Nitrotoluene; Hexahydro-1,3,5-Trinitro-1,3,5-Triazine]; (b) concentrations of these substances in fish and lobster tested do not exceed EPA's Risk Based Concentrations for commercially edible seafood, but (c) concentrations of these substances in several of the non-commercial species tested (e.g. feather duster worms, corals, and sea urchins) greatly exceed these concentrations. For chromium in sediments, and for TNT in both water and sediment, there is an exponential decline with increasing distance from unexploded ordnance. An organism's mobility and proximity to UXO determine its body burden of toxic compounds: (1) the closer an organism is to a

leaking bomb, the higher its body burden will be, and (2) the less mobile (and therefore more sessile) an organism is, the higher the concentration of toxic substances will be.

Our data show unequivocally that toxic substances leaching from UXO have entered the coral reef marine food web. Since the concentration of explosive compounds is highest near unexploded ordnance, we recommend that surface UXO on the Vieques coral reef be picked up and removed. We assert that this action will have an immediate and beneficial effect on the coral reef ecosystem by removing these point sources of pollution from the environment. Existing technology can perform this required action easily.

Keywords

Coral reefs Ecotoxicology Carcinogens Explosive compounds Underwater ordnance UXO Puerto Rico Vieques

Introduction

Both the preparation for and conduct of war are environmentally destructive. While the financial and human costs of war are readily acknowledged, the environmental costs of war are rarely recognized, let alone quantified. Machlis and Hanson [50] point out that in the past two decades there have been 122 armed conflicts and that 85% of the 192 sovereign nations on earth maintain standing armies [38,50,51]. Further, the preparation for war consumes 6% of raw materials and produces as much as 10% of global carbon emissions annually [17,18,50,51]. Bidlack [17] estimates that military instillations and bombing ranges cover 15 million $km^2$of the earth's surface.

Isla de Vieques, Puerto Rico is one of these places. Vieques is situated off the eastern end of Puerto Rico and lies within the 100 m depth contour of the Puerto Rican rise. Vieques is substantially larger than St. Thomas and only slightly smaller than St. Croix, US Virgin Islands. The island is partitioned into three sectors (Fig.1[top]): the Eastern Naval Area, on the eastern end of the island (Fig.1[bottom]), the Naval Ammunition Facility on the western end, and the Civilian Area in the middle. With almost two-thirds of the island designated as restricted areas, the island is unique in the Caribbean in having almost 100 miles of uninhabited coastline. Vieques has been used for naval training exercises since 1941. Beginning in 1999, formal requests were made by the Puerto Rican government to the US Navy to cease military operations on Vieques [11]; naval exercises ceased entirely in May, 2003 [15].

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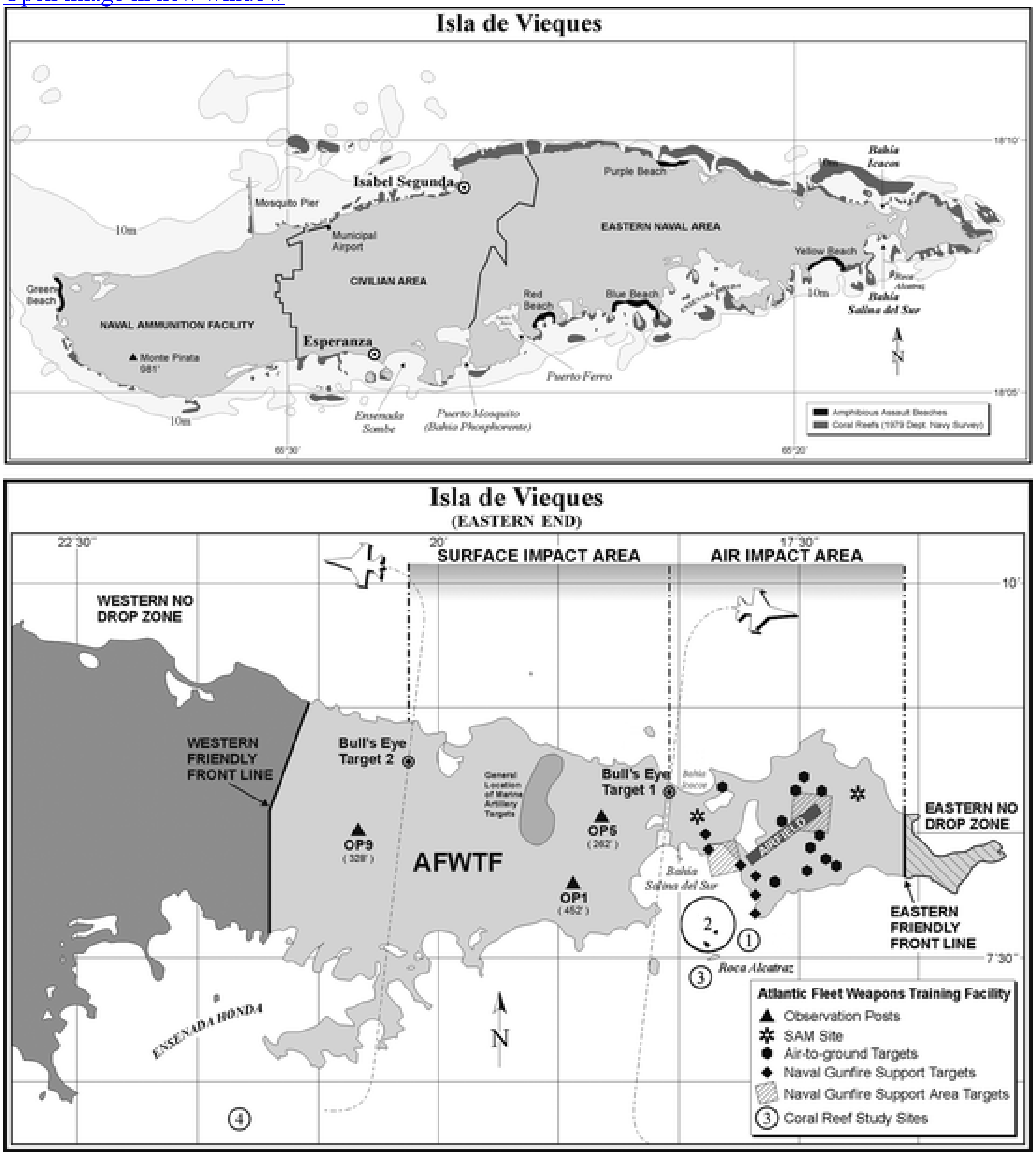

Fig. 1

(*Top*) Map of Isla de Vieques, Puerto Rico. The Naval Ammunition Facility occupies the western third of the island. The Civilian Area sits in the center, with its two fishing villages, Esperanza and Isabel Segunda, and separates the Ammunition Facility area from the Eastern Naval Area, which occupies the remaining third of the island and includes the Live Impact Area and bombing ranges. The position of the subtidal 10 m depth contour is demarcated by a dashed line. Biological features such as fringing reefs and bioluminescent bays, and the location of live-fire amphibious assault beaches are also shown (Adapted from: Department of the Navy. 1979. Draft Environmental Impact Statement. Volume II, Maps 3, 19, 21, 26, and 30). (*Bottom*) Map of the eastern end of Isla de Vieques, Puerto Rico. This area encompasses the bombing range, military targets, flight-path approaches, the “Eastern No Drop Zone,” and observation posts within the Atlantic Fleet Weapons Training Facility (AFWTF). Samples were collected for radiological and chemical analysis at the two USN*Killen*wreck sites: Site 1 (the*Killen*bow) at 18° 07.5 N; 65° 18.2 W and Site 2 (the*Killen*stern) at 18° 07.6 N; 65° 18.2 W; and in and around Site 3, an unexploded General Purpose 2,000 lb bomb located just seaward of Roca Alcatraz at 18° 07.4 N; 65° 18.1 W (Adapted from: Department of the Navy. 1979. Draft Environmental Impact Statement. Volume II, Maps 3, 19, 21, 26, and 30)

Air-Dropped Bombs and Artillery Shells

The amount of bombs and other explosives dropped and detonated on the eastern end of Vieques is staggering (Table1). US Navy Vice Admiral Hohn Shanahan estimated that during the 20 years between 1980 and 2000, the Navy dropped approximately 3 million pounds of live ordnance on Vieques every year [86]. Extrapolating this amount over the 63-year history of the bombing range results in an estimate of 189 million pounds (85 million kg) of high explosives detonated on Vieques prior to base-closure in 2003. However, more recent government inventories reveal that, rather than 3 million pounds per year, an average of 14 million pounds of ammunition were dispensed by the Vieques Ammunition Storage Depot in both 1993 and 1994 [86]. This rate is almost five times the earlier estimate, suggesting that the cumulative estimate of 189 million pounds used in the Atlantic Fleet Weapons Testing Area (Fig.1[bottom]) may be a substantial underestimate.

Table 1

Best estimates of the kinds, rates, and totals of munitions dropped within the Live Impact Area on the eastern end of Vieques, Puerto Rico, from 1943–2003

Vieques munitions			
	Rates	**Totals**	**Source**
Operations	180–250 days/year (χ = 100 days/year)	6,300 bombing days	[8] [86]
Kinds	Radiological weapons		[82]
	Depleted uranium	267 rounds/88 lb	[86, p 100]
	Chemical weapons		
	Napalm		[5]
	Agent orange		[5]
	Rocket fuel	7,000 lb	[5]
	Diesel (ocean spills)	100,000 gal	[86]
	Biological weapons	Program acknowledged, but without specific detail of time, place, or agent(s)	[81] [86]
	Conventional weapons High explosives		[9]
Numbers	7,6000 bombs/month	$1*10^6$bombs	[77]
Amounts	$3*10^6$lb/year	$189*10^6$lb	[77]
	$14*10^6$lb/year	$662*10^6$lb	[82] [86, p 97]
Water hits	100/decade (1990–2000)	6,300 water hits	[86]
	45,000 (1943–1980)	100,000 UWUXO	[77]
		$2*10^6$lb of UWOXO	[86, p 97]

In 1979, during peak training exercises, 7,600 bombs were dropped on the island per month [86] (Table1). Bombing intensity increased in the 1970s because the US Congress closed the bombing range on nearby Culebra Island. In a Congressionally mandated Environmental Impact Statement [77], the US Navy published the density of live air-dropped bombs (Fig.2[top]) and estimated that only 5% of this ordnance fell into near-shore waters. This estimate still leaves 45,000 bombs lying on Viequean coral reefs and sea grass beds. By the Navy's own estimate, 72,000 lb of explosives were dropped into near-shore waters, leading to a cumulative 30-year estimate of well over 2 million pounds of ordnance lying in the shallow coastal waters of Vieques.

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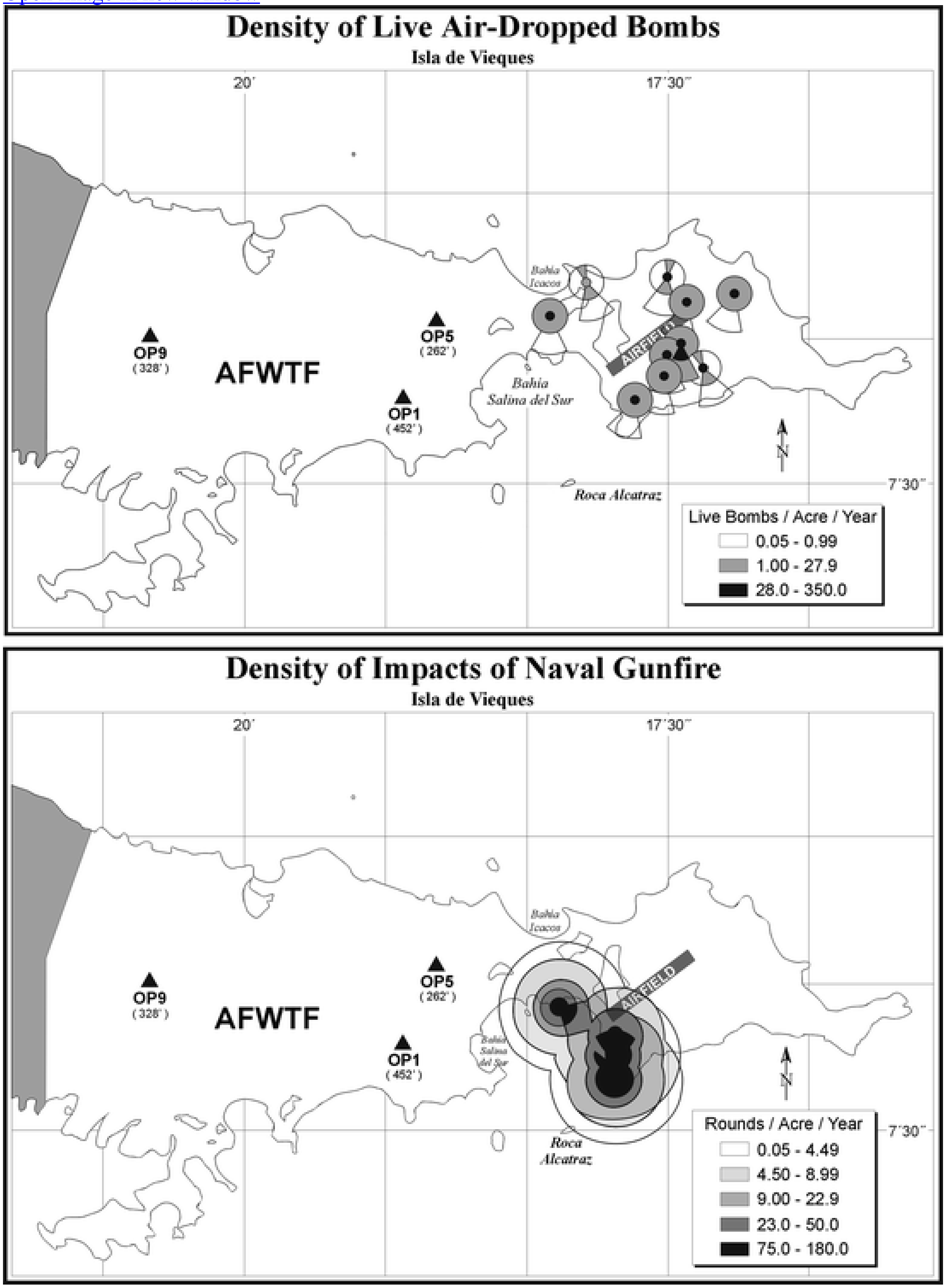

Fig. 2

(*Top*) Map of the density of live air-dropped bombs aimed at land-based targets on the eastern end of Isla de Vieques, Puerto Rico. The data are expressed in terms of live bombs/acre/year in the zones of highest impact, but do not include information on less frequent, but environmentally important, misses in which bombs fell in near-shore sea grass beds and on off-shore coral reefs. This map also does not show any of the bombing targets floated over, and as a consequence sunk onto, the coral reef (Adapted from: Department of the Navy. 1979. Draft Environmental Impact Statement. Volume II, Map 39). (*Bottom*) Map of the density of naval gunfire aimed at land-based targets on the eastern end of Isla de Vieques, Puerto Rico. Data are expressed in terms of rounds/acre/year in the zones of highest impact, but do not show the density of less frequent misses in which artillery shells fell far from the mark, landing in near-shore sea grass beds and on off-shore coral reefs. This map also does not show any of the targets floated over the reef (such as the USN*Killen*) and used for gunnery practice (Adapted from: Department of the Navy. 1979. Draft Environmental Impact Statement. Volume II, Map 38)

Naval shelling exercises on Vieques were also intense. Annually, between 120 and 130 US and allied ships targeted Vieques with naval gunfire. Live-fire exercises were conducted on Vieques between 180 and 250 days per year. This includes naval shelling activities, which averaged more than 100 days per year [86]. The majority of the ordnance used during these exercises was 2- to 5-inch artillery shells, but Vieques was also targeted with 18-inch shells from the largest battleships in the fleet. The Navy estimated [77] that 40% of the shells fired missed their land targets and fell in coastal waters (Fig.2[bottom]). Conservatively, this means that, with millions of rounds fired, hundreds of thousands of these fell on coral reefs and other marine habitats near shore.

USN*Killen*

The possibility of radioactive contamination on Vieques coral reefs was raised by the presence of the sunken vessel, the USN*Killen*. The*Killen*was a Fletcher Class Destroyer [Hull Nr. DD-593] launched on January 10, 1941 [22]. The vessel was decommissioned and mothballed in San Diego Harbor on July 9, 1946. The*Killen*was reactivated as a trial ship in 1958 and used as a target during the Hardtack, Wahoo, and Umbrella atomic bomb tests in the US Marshall Islands. During the detonations, the ship rolled several times but somehow righted itself and survived. Information provided by the Navy states that the*Killen*underwent a water wash after the atomic blasts to remove as much of the radioactivity as possible. A few days after each test, crews went on board, surveyed the ship, and manually decontaminated those areas needing additional treatment [7]. There is no indication that sandblasting was used in the decontamination process. After cleaning, the ship was brought back across the Pacific, through the Panama Canal, and used in high explosive tests in Chesapeake Bay in 1962. The*Killen*was taken to Puerto Rico and officially struck from the Navy List in January 1963. It was docked at Roosevelt Roads when not in use as a bombing range target on Vieques. In 1975, the*Killen*was towed to Vieques and scuttled in Bahia Salina del Sur near the Live Impact Area (LIA) due north of Isla Alcatraz (Fig.1[bottom], Site 2).

Although the downward-looking profile of the combined wreck sites is that of a destroyer, the profile is not, and we must assume that the superstructure of the ship, including all armaments, was either removed before towing it to the bombing range on Vieques, or blasted away during the ship's use as a target. Deslarzes et al. [24] speculate that the superstructure, and much of the upper decking, was removed prior to its use on Vieques as a target, and that the barrels found inside the sunken vessels were used as flotation devices to "extend the*Killen*'s usefulness as a surface target."

The USN*Killen*presently lies on the bottom of Bahia Salina del Sur in two sections in water approximately 30 ft deep. The fore section (Fig.3[top]) was especially badly damaged during target practice; the aft section (Fig.3[bottom]) is mostly intact. Both sections of the wreck are surrounded with a fine- to coarse-grained carbonate sand bottom.

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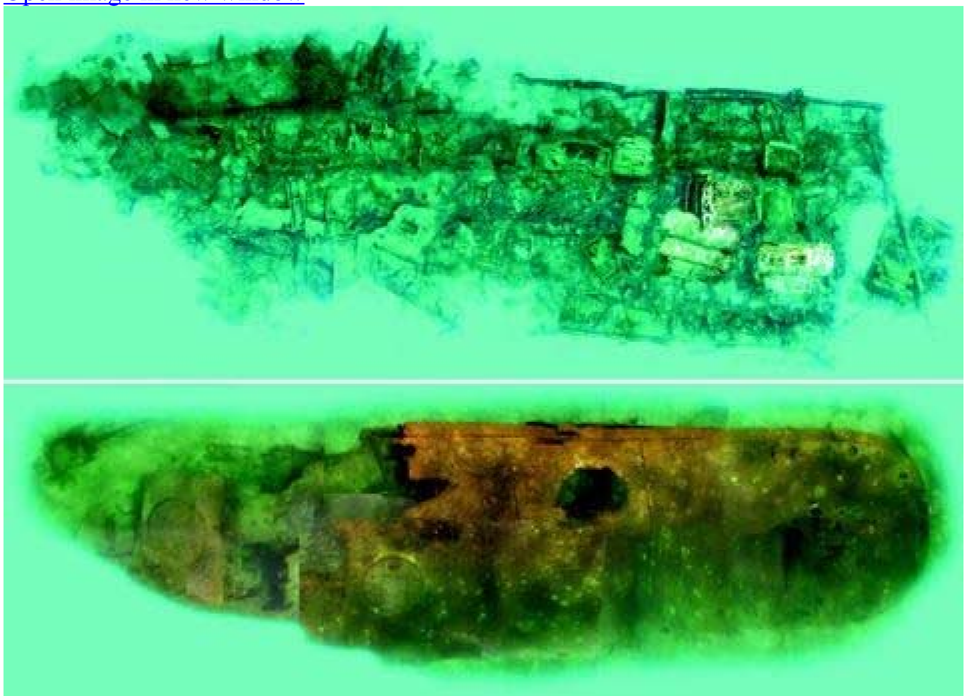

Fig. 3

The USN*Killen*bow (*top*) and stern (*bottom*) sections in Bahia Salina del Sur, Vieques, Puerto Rico

In addition to concerns over the radiological status of the USN*Killen*, the US Navy admitted to strafing the eastern end of the island with 267 rounds (88 lb) of armor-penetrating depleted uranium ammunition [86]. Because the use of radioactive munitions required special permission from the US Nuclear Regulatory Commission (which had not been obtained), the Navy attempted to recover the material. Although approximately half of the depleted uranium shell casings were located (only from land sites), none of the radioactive material contained in them was found, leading to concern that radioactive materials from this depleted uranium ordnance may also have spread into the marine environment.

Previous Research on Vieques

Site Characterization

As access to, and environmental concerns about, marine habitats on Vieques have increased, the number and sophistication of environmental surveys on this area have also increased. Starting in the late 1970s [2, 3, 4,71,73], investigators focused on the obvious signs of damage in the LIA. These include the presence of live ordnance, including 2,000 lb bombs (Fig.4[upper left]), cratering (Fig.4[upper right]), explosive compounds leaching from corroding ordnance (Fig.4[lower left]), and a diverse and abundant plethora of military debris, parachute flares, mortars, rocket fin assemblies, machine-gun bullets, and unexploded battleship artillery rounds. Later studies attempted to quantify the impact as a function of distance from the epicenter of military activity [66,67]. Local [24,32,39,45] and region-wide comparisons followed [72].

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Fig. 4

(*Upper left*) Underwater unexploded ordnance (UWUXO) in high concentrations litters the seafloor in many areas around the world. Photograph shows a 2,000 lb General Purpose air-dropped bomb located at Site 3 (Fig.1[bottom]) just south of Roca Alcatraz within the US Naval bombing range, Isla de Vieques, P.R. This ordnance had several corrosion holes located in its mid-section exposing the contents of the bomb to the surrounding seawater. (Photograph by Dr. James W. Porter) (*Upper right*) Bomb craters pock mark coral reefs on the seaward side of Bahia Salina del Sur, Isla de Vieques, P.R. All craters investigated in the magnetometer survey were perfectly symmetrical holes, approximately 14 m in diameter and 1.5 m deep, such as this typical crater 50 m south of Roca Alcatraz (18° 07′ 21.60″ N; 065° 18′ 03.50″ W). (Photograph by Dr. James W. Porter) (*Lower left*) High explosives from within the cavities of a corroding bomb on the Vieques coral reef spill and leach out onto the surrounding reef. The granular material from these unexploded munitions was analyzed for TNT, Semtex, C-4, and other high explosive compounds. (Photograph by Dr. James W. Porter) (*Lower right*) Diseased colony of the mountainous star coral (*Montastraea faveolata*) in physical contact with a leaking bomb. Samples of this colony detected the presence of exceptionally high concentrations of explosive compounds. (Photograph by Dr. James W. Porter)

Since mechanical destruction from bombing and military activity is quite localized, the spatial and temporal scale of the analysis determines the observations made and the conclusions drawn. One can demonstrate that the impact from military activity is high if the time scale is short (and includes a bombing exercise) or if the spatial scale is small (and includes an area affected by live-fire). Alternatively, since hurricanes and disease have occurred throughout the Caribbean over the last several decades [72], long timeframes and broad spatial scales reveal absolutely nothing. However, as can be seen from aerial photographs (Fig.5) of the cratered moonscape of the Viequean fore-reef in the LIA, this was not a place to be during bombing exercises.

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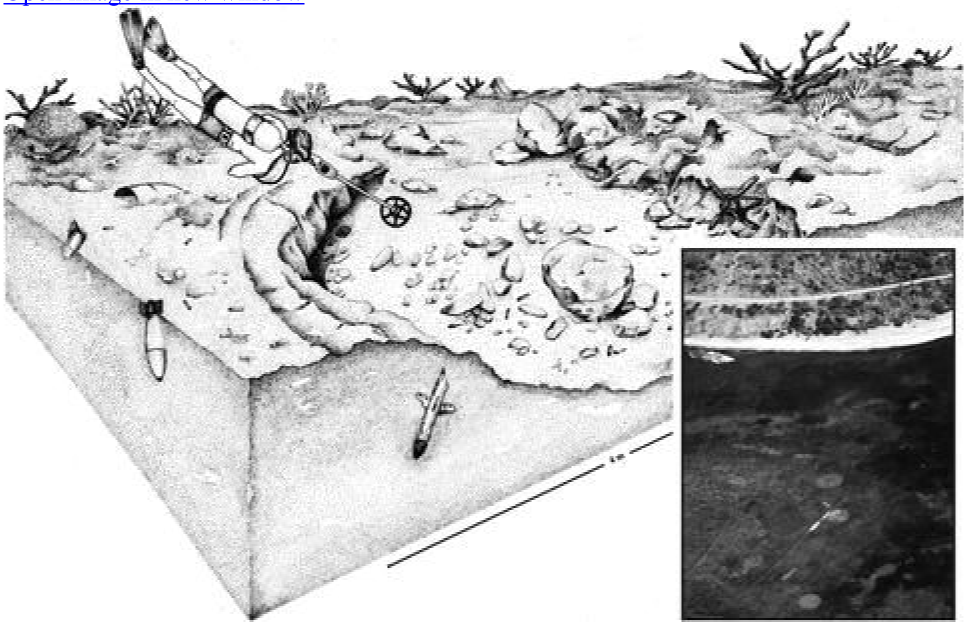

Fig. 5

Artist’s rendition of a bomb crater cross-section from a Viequean coral reef. Most of the metallic objects in the crater walls are invisible to the naked eye, but their presence in fissures and stress fractures is revealed by the metal detector. (Drawing by Andrew Sutherland)

More recently, studies have focused on the trace elements of marine and terrestrial plants in the region [25,53]. These investigators found high lead concentrations in *Syringodium filiforme* (manatee grass) from bays in the LIA, indicative of dispersion of pollution and bioaccumulation of hazardous materials within the marine food chain.

The Designation of Vieques as a Superfund Site

In August, 2005, the US Environmental Protection Agency designated the Atlantic Fleet Weapons Testing Facility (AFWTF) (Fig.1[bottom]) as a Superfund Site, stating, “The AFWTF Facility includes land areas, waters, and cays in and around the islands of Vieques and Culebra impacted by 100 years of military training operations, largely by the US Navy. The Navy used the eastern portion of Vieques for training from the 1940s until it ceased operations there on May 1, 2003. Areas of Culebra were used for military exercises from 1902 until July 1975. Contaminants of the land and water resulting from these activities may include mercury, lead, copper, magnesium, lithium, perchlorate, TNT, napalm, depleted uranium, PCBs, solvents, and pesticides” [15].

In February, 2005, citing heightened safety concerns, the waters surrounding Vieques were added to EPA’s National Priorities List of Superfund Sites. The Pentagon oversees about 140 of the current 1,240 toxic Superfund sites and is actively cleaning up more than 100 of these under the CERCLA/Superfund Site Program [15]. However, as this paper goes to press, we know of no efforts or plans to clean up subtidal areas of Vieques.

Designation of the Former Bombing Range as a National Wildlife Refuge

A large proportion of the former US Naval Bombing range has been designated as a National Wildlife Refuge within the US Department of the Interior. This conservation action created the largest national wildlife refuge in the Caribbean. Proposed open-air detonation of unexploded ordnance (UXO) on land [9], however, means that extirpation of live ordnance from Vieques is still incomplete. Aerial disposal of this ordnance will further expose both marine and terrestrial environments to UXO degradation and detonation products.

Human Health Concerns on Vieques

Most research on the existence and distribution of toxic materials in the environment is focused almost exclusively on identifying pathways that lead directly to humans. Studies on Vieques are no exception [6, 7, 8]. While not the focus of our study, we acknowledge the well-documented health concerns that exist on Vieques [57]. Relative to populations on the mainland of Puerto Rico, with similar demographics, long-term Vieques residents have elevated (1) incidence and mortality from cancer, (2) hypertension, (3) asthma, (4) diabetes, (5) epilepsy, and (6) cardiovascular disease [86]. In addition, recent studies on the mercury content of human hair [61] have shown elevated heavy metal concentrations among reproductive-age women.

Purpose of this Study

The objective of this paper is to present the ecological, radiological, and toxicological findings of our research on Vieques. In this study, we were especially interested in attempting to name and quantify man-made toxins on this coral reef, to pinpoint the location of these hazardous materials, and to begin to describe the pathways and ecosystem effects of these hazardous compounds. Further, we wished to assess the radiological status of the USN*Killen*and determine if its use in mid-Pacific atomic bomb tests had brought radiological hazards onto this Caribbean coral reef.

Materials and Methods

Ecological Surveys

Swim surveys around Vieques revealed that the most extensive reef development occurs at the eastern end of the island, within the naval bombing range (Figs.1and2). At three localities, Bahia Salina del Sur, Roca Alcatraz, and Ensenada Honda (Fig.1[bottom], Sites 1, 3, and 4), we conducted standardized EPA coral species inventories [70] within paired belt transects. Each belt transect was 20 m long and 2 m wide. The surveys consisted of colony counts for all coral species present, the presence of coral bleaching or disease [70], the number of the herbivorous sea urchin (*Diadema antillarum*), and the number of the commonest sea fan (*Gorgonia ventilina*) within the transect area. Types and amounts of underwater unexploded ordnance (UWUXO) (Fig.4[upper left]) and other military debris were also enumerated.

Magnetometer Surveys

Without destructive and potentially hazardous excavation, it is impossible to determine the composition, mass, and burial depth of metallic objects and UWUXO embedded in the reef. In response to this sampling challenge, we used a Fischer Portable Underwater Magnetometer [30] to survey crater sites on Vieques (Fig.4[upper right]). When a metallic object embedded in the reef is detected, both auditory (beeping) and visual (flashing lights) signals indicate its presence. The crater (Fig.4[upper right]) was divided into 30° quadrants. The magnetometer operator swung the magnetometer back and forth slowly in front of the crater wall within each quadrant at increasing distances from the wall. The maximum distance that triggered a detection response was recorded for each of the 12 quadrants around the crater. The magnetometer's response was unambiguous: after the magnetometer first registered a response, it continued to register a response as the magnetometer was moved closer to the wall, but never registered a response if the magnetometer was moved farther away from the first response distance.

Larger objects triggered the response at greater distances from the magnetometer head than smaller objects. For calibration purposes, we assumed that every object embedded in the crater and detected by the magnetometer was a spherical steel ball buried 2 cm below the surface. The distance from the crater wall that the magnetometer registered a response was calibrated as the mass of a steel object buried 2 cm below the surface. Positive responses at greater distances suggest greater mass. We are well aware of the limitations of this calibration technique. For instance, large objects buried deeply would trigger the same response as small objects buried shallowly. For this reason, we are calling this calibration unit the minimum mass. From our calibration curve, if the magnetometer registers the presence of a metallic object when the magnetometer is held 10 cm from the crater wall, then the minimum mass would be a steel sphere weighing 40 g buried 2 cm beneath the crater wall. Only destructive sampling could reveal the actual mass of a buried object.

Radiological Analyses

To determine if radiological health risks were associated with the area or its natural resources, the expedition used a variety of alpha, beta, and gamma-emitting radionuclide detectors. The priority isotopes of concern were those related to nuclear fallout or fission products from nuclear testing in the 1950's and 1960's [Cobalt-60 (^{60}Co 5.3 year half-life), Strontium-89 (^{89}Sr 51 day half-life), Strontium-90 (^{90}Sr 28 year half-life), Krypton-95 (^{95}Kr 10.3 year half-life), Zirconium-95 (^{95}Zr 65 day half-life), Ruthenium-103 (^{103}Ru 40 day half-life), Iodine-131 (^{131}I 8 year half-life), and Cesium-137 (^{137}Cs 30 year half-life)]. However, all gamma spectra were analyzed with a nuclide library containing 110 known nuclides. The instrumentation included: Ludlum Model 2241 with a 44–9 GM detector [(alpha – very limited, beta, and gamma) (instrument range: 0–500,000 cpm)]; Ludlum Model 2241 with a 43–93 Scintillator [(alpha and beta) (instrument range: 0–500,000 cpm)]; Ludlum Model 19A MicroR [(gamma) (instrument range: 0–500 mr/h)]; Ludlum Model 9 Ion Chamber [(beta and gamma) (instrument range: 0–5,000 mr/h)]; FieldSPEC with a NaI detector [gamma (measures energy spectrum) (instrument range: ∼50–2,000 kev)]; and an XRF 4000 with a CdT_ldetector [gamma (measures energy spectrum) (instrument range: ∼50–2,000 kev)]. Three environmental radiation thermoluminescent detectors (TLDs) were deployed underwater for 72 h near the USN*Killen*bow and stern (Fig.3[top and bottom]).

To ensure the safety of the dive teams, gamma scans were conducted at each dive site. The XRF 4000 was also used to record energy spectra from several underwater dive locations including both the submerged bow and the stern sections of the USN*Killen*(Fig.3[top and bottom]).

In the field, water, sediment, coral, and fish were collected at Sites 1–3 (Fig.1[bottom]) to assay for radiological contamination. Each sample was given a unique identification number and entered into a chain of custody record. Water and sediments were collected at depth in 1-liter wide-mouth, clear plastic jars. At the surface, these samples were transferred to Marinelli beakers.

Living brain coral (*Diploria labyrinthiformis*) and mountainous star coral (*Montastraea faveolata*) were collected from the sites and also stored in Marinelli beakers.*D. labyrinthiformis*heads were chiseled from the USN*Killen*superstructure. This method removed the entire coral head in one piece plus a layer of metal from the ship. The metal layer attached to the bottom of the coral was removed and processed for potential gamma radioactivity.

Fish samples were collected using a spear gun and bagged until delivery to the surface whereupon they were cut into small pieces and homogenized in a stainless steel blender before storage. Fish samples included French angel fish, blue tangs, French grunts, red hinds, and yellowtail snappers from both the bow and stern sections of the USN*Killen*. A total of 11 fish were collected at the two sites. Fish samples collected for radiation analyses were also analyzed for explosive and heavy metals. Due to the relatively large sample size required for radiation determination, all fish from each site were composited in the laboratory to form one sample per site.

All Marinelli beaker samples were sealed with vinyl tape and stored for a minimum of 14 days before analysis to allow for the in-growth of naturally occurring uranium (U) and thorium (Th) daughter products.

All samples collected during the survey were packed in coolers filled with ice and delivered to an overnight carrier for transport to The University of Georgia's Agricultural and Environmental Services Laboratory in Athens, Georgia where the samples were divided for metals, explosives, and radiological analyses. Radiological samples were then transferred to the University of Georgia's Center for Applied Isotope Studies.

In the laboratory, gamma radiation measurements were acquired using a Canberra High Purity Germanium (HPGe) detector, Model GC 40195 coupled to a Canberra InSpector, 8,000-channel spectrometer, operating at 4000 V. The gamma radiation spectrum was acquired from a 12,000 s count and downloaded to Canberra's Genie 2000, Version 2 software. Gamma spectra are reported as picocuries per kilogram (pCi/Kg).

Sediment samples were individually placed in stainless steel containers and oven dried at 60°C. After reaching complete dryness, samples were ground to 3 mm or less particle size, packed into a tared 0.5-L Marinelli beaker, and weighed. Coral samples were dried in the same manner. Bleaching of the corals was not incorporated into the analytical protocol in an attempt to retain coral tissue in the sample. A ceramic-tooth rock crusher was used to break the coral into small particles.

Chemical Analyses

The eastern end of Vieques is littered with UXO and other military debris. At both USN*Killen*wreck sites in Bahia Salina de Sur and at Roca Alcatraz, we collected water, sediment, fish and coral, and analyzed these for explosive compounds and heavy metals (Table2) using the following block sampling design: 3 locations × 2 samples per location × 4 matrices (water, sediment, coral, fish). At Alcatraz, we also collected a suite of physical and biological samples from inside, and at increasing distances from, a corroding bomb (Fig.4[upper left and lower left]; Tables2and3).

Table 2

Munitions residues, arsenic (As), lead (Pb), and mercury (Hg) concentrations at several coral reef locations, Isla de Vieques, Puerto Rico (Fig.1[bottom])

	***USN Killen*bow (Fore Section; Site 2a)**				***USN Killen*bow (Aft Section; Site 2a)**				***USN Killen*stern (Site 2b)**			
	Munition residue	**As**	**Pb**	**Hg**	**Munition residue**	**As**	**Pb**	**Hg**	**Munition residue**	**As**	**Pb**	**Hg**
Water	<1.3– < 1.7ppb	2.51 μg/L	2.06 μg/L	0.48 μg/L	<1.3– < 1.7 ppb[a]	1.15–1.38 μg/L	<0.56–0.73 μg/L	<0.08–0.09 μg/L	<1.3– < 1.7 ppb	0.93–1.02 μg/L	0.70–0.77 μg/L	<0.08 μg/L
Sediment	<1.2– < 1.3mg/kg[b]	5.24 mg/kg	5.18mg/kg	<2.10 mg/kg	<0.5 mg/kg	1.75 mg/kg	<2.4 mg/kg	<2.10 mg/kg	<1.2– < 1.3 mg/kg	3.17–5.99 mg/kg	4.22–80.3 mg/kg	<2.10 mg/kg
Fish	<0.5 mg/kg[c]	0.76 mg/kg[d]	<2.65 mg/kg	<1.20 mg/kg	–	–	–	–	<0.5– < 1.3 mg/kg	1.05 mg/kg[d]	<2.65 mg/kg	<1.20 mg/kg
Coral	<0.5 mg/kg	<0.20 mg/kg	8.14 mg/kg	<1.25 mg/kg	<0.5 mg/kg	<0.20 mg/kg	<4.9 mg/kg	<1.25 mg/kg	<0.5–252 mg/kg	<0.20–0.91 mg/kg	20.5–88.0 mg/kg	<1.25 mg/kg
Lobster	<0.5 mg/kg	38.4 mg/kg[d]	<2.65 mg/kg	<1.20 mg/kg	–	–	–	–	–	–	–	–

	Roca Alcatraz (Site 3)				**Hatillo, PR (Control)**			
	Munition residue	**As**	**Pb**	**Hg**	**Munition residue**	**As**	**Pb**	**Hg**
Water	<1.3– < 1.7 ppb	1.30–1.42 μg/L	0.62–0.63 μg/L	<0.08–0.09 μg/L	<1.3– < 1.7 ppb	–	1.02 μg/L	0.08 μg/L
Sediment	354–4,380 mg/kg	1.28–1.90 mg/kg	<2.40 mg/kg	<2.10 mg/kg	<1.2– < 1.3 mg/kg	4.22 mg/kg	32.3 mg/kg	<2.10 mg/kg
Fish	4.6 mg/kg [e]	–	–	–	–	–	<2.65 mg/kg	<1.20 mg/kg
Coral	<0.5 mg/kg	0.41 mg/kg	195 mg/kg	<1.25 mg/kg	<0.5 mg/kg	<1.13 mg/kg	126 mg/kg	<1.25 mg/kg
Lobster	–	–	–	–	–	–	–	–

Munition samples were analyzed by immunoassay and HPLC. Positive samples contained primarily TNT as the explosive residue. The EPA Risk-Based Concentration (RBC) for TNT in fish is 0.11 mg/kg. The EPA Drinking Water Maximum Contaminant Level (MCL) value for As is 50 μg/L, for Pb is 15 μg/L, and for Hg is 2 μg/L. The EPA Risk-Based Concentration (RBC) for As in fish is 0.26 mg/kg and 0.16 mg/kg in lobster. The RBC for Pb is 0.03 mg/kg in both fish and lobster. The RBC for Hg in fish is 1.0 mg/kg. The control fish is from a local Kroger, Athens, GA.

– No sample taken

[a]One water sample near the*USN Killen*bow was positive for RDX by immunoassay but presence of RDX could not be confirmed by HPLC

[b]One sediment sample near the*USN Killen*bow showed trace quantities (0.5–1.5 mg/kg) of TNT by immunoassay, but this could not be confirmed by HPLC

[c]One of the two duplicate fish composite samples from Site 2a gave a positive response for RDX in the immunoassay, but this could not be confirmed by HPLC

[d]Exceeds EPA's allowable Risk Based Concentration for arsenic (As) in seafood (0.26 mg/kg for fish and 0.16 mg/kg in lobster)

[e]4.6 mg/kg 1,3,5-Trinitrobenzene detected in damselfish sample from vicinity of the bomb; TNT and RDX were not detected in this fish sample

Table 3

Concentrations of explosive compounds detected in biota, water, and sediments sampled on Isla de Vieques

	1,3,5-Trinitrobenzene		**1,3-Dinitrobenzene**		**2,4,6-Trinitrotoluene**		**2,4-Dinitrotoluene +2,6-Dinitrotoluene**		**4-Nitrotoluene**		**2-Nitrotoluene**		**Hexahydro-1,3,5-Trinitro-1,3,5-Triazine**	
	Detected concentration	**EPA RBC for fish**	**Detected concentration**	**EPA RBC for fish**	**Detected concentration**	**EPA RBC for fish**	**Detected Concentration**	**EPA RBC for Fish**	**Detected concentration**	**EPA RBC for fish**	**Detected concentration**	**EPA RBC for fish**	**Detected concentration**	**EPA RBC for fish**
Feather duster worm Rocas Alcatraz *Sabellastarte magnifica*	23.9 mg/kg	41 mg/kg	9.52 mg/kg[a]	0.14 mg/kg	40,200 mg/kg[a]	0.11 mg/kg	N/D		95.5 mg/kg[a]	14 mg/kg	N/D		N/D	
Dusky damselfish Rocas Alcatraz *Stegastes adustus*	4.6 mg/kg	41 mg/kg	N/D		N/D		N/D		N/D		N/D		N/D	
Coral *Montastraea faveolata* Rocas Alcatraz – 0.1 m from bomb	250 mg/kg[a]	41 mg/kg	250 mg/kg[a]	0.14 mg/kg	600 mg/kg[a]	0.11 mg/kg	250 mg/kga	14 –27 mg/kg	N/A		N/A		N/A	
Coral *Diploria*	N/D		N/D		N/D		N/D		N/D		N/D		N/D	

	1,3,5-Trinitrobenzene		1,3-Dinitrobenzene		2,4,6-Trinitrotoluene			2,4-Dinitrotoluene +2,6-Dinitrotoluene	4-Nitrotoluene		2-Nitrotoluene		Hexahydro-1,3,5-Trinitro-1,3,5-Triazine	
	Detected concentration	**EPA RBC for fish**	**Detected concentration**	**EPA RBC for fish**	**Detected concentration**	**EPA RBC for fish**	**Detected Concentration**	**EPA RBC for Fish**	**Detected concentration**	**EPA RBC for fish**	**Detected concentration**	**EPA RBC for fish**	**Detected concentration**	**EPA RBC for fish**
*labyrinthiformis*Rocas Alcatraz – 15 m from bomb														
Coral														
Diploria labyrinthiformis On*USN Killen*hull	N/D		N/D		252 mg/kg[a]	0.11 mg/kg		N/D	N/D		N/D		N/D	
Long-spined sea urchin														
Rocas Alcatraz *Diadema antellarum*	N/D		N/D		721 mg/kg[a]	0.11 mg/kg		N/D	N/D		N/D		N/D	
Sediment														
Rocas Alcatraz – 0.0 m from bomb	30.7 mg/kg		3.47 mg/kg		19,333 mg/kg			26.0 mg/kg	5.39 mg/kg		N/D		5.32 mg/kg	
	Detected Concentration	EPA RBC Water	Detected Concentration	EPA RBC Water	Detected Concentration	EPA RBC Water	Detected Concentration	EPA RBC Water	Detected Concentration	EPA RBC Water	Detected Concentration	EPA RBC Water	Detected Concentration	EPA RBC Water
Water														
Rocas Alcatraz – 0.0 m from bomb	11,525 ppb[b]	1,100 ppb	18,500 ppb[b]	3.7 ppb	85,700 ppb[b]	2.2 ppb	82,500 ppbb	37–73 ppb	N/D		40,500 ppb[b]	61 ppb	4,120 ppb	N/A
Water														
Rocas Alcatraz – 0.1 m from bomb	8.15–14.9 ppb	1,100 ppb	13.6–23.4 ppb[b]	3.7 ppb	66.4–105 ppb[b]	2.2 ppb	58–107 ppbb	37–73 ppb	N/D		26.4–54.6 ppb	61 ppb	N/D	N/A

*Montastraea faveolata*data provided by Dr. Fred Hovercamp, Reactive & Explosive Materials, Corp.

*RBC*Risk Based Concentration,*N/A*Not analyzed,*N/D*Concentration below detection limits

[a]Concentration Detected Exceeds EPA's RBC for Fish

[b]Concentration Detected Exceeds EPA's RBC for Tap Water

As with the radiological sampling, divers collected water, sediment, coral, and fish at each of the three survey sites. Water samples were collected in 1-L amber glass jars with Teflon-lined caps. Sediments for heavy metal and explosive analysis were collected in 250-ml amber high-density polyethylene jars and 500-ml amber glass jars, respectively. Coral and fish samples collected for radiation analyses were also utilized for explosive-compound and heavy metal contamination. All fish from each site were composited in the laboratory to form one sample per site.

To test for the presence of heavy metals and explosive compounds in and around UXO, collections of bomb leachate, water, sediments, fish, coral, and selected invertebrates were made in, and adjacent to, UXO on the fore-reef slope seaward of Isla Alcatraz in Bahia del Sur (Fig.1[bottom], Site 3). A non-magnetic stainless steel auger was used to scrape bomb leachate from the inside of a corroded 2000-pound GP (General Purpose) bomb. Long-nose forceps and test-tube tongs were then used to remove solid materials that had been scraped off the interior walls inside the bomb (Fig.4[lower left]). Much of the material removed from the bomb had the consistency and appearance of peanut brittle or Baltic amber. Pieces of this UXO material were dropped into wide-mouth amber glass jars, sealed underwater, and brought to the surface for shipment. Both sediments and water in the vicinity of the bomb were collected at distances of 0.00, 0.01, 0.10, 1.00, and 2.00 m from the ordnance. Water was collected in amber glass jars. Sediment was acquired using a large Nalgene pipette that collected the full range of sediment sizes present at each locality.

Bombs located in and around Site 3 had many solution cavities up to 20 cm in diameter and had become "artificial reefs" for several mobile and sedentary reef organisms. A specimen of the territorial dusky damselfish,*Stegastes adustus*, was collected from one cavity. In addition, a feather duster worm,*Sabellastarte magnifica*, attached to the bomb (Fig.4[upper left]), and a long-spined sea urchin,*Diadema antillarum*, grazing on top of the bomb, were sampled. Specimens of the star coral,*Montastraea faveolata*,physically adjacent to the bomb (Fig.4[lower right]), and a brain coral,*Diploria labyrinthiformis*,15 m from the bomb were also collected.

All samples were brought to the surface, packed in ice, and shipped to the University of Georgia Agricultural and Environmental Services Laboratory (AESL) in Athens, GA. Delivery times ranged from 1 to 4 days, but coolers were <4°C upon receipt at the AESL. In the laboratory, solid samples were stored in a walk-in freezer (<−20°C) until analysis. Water samples were stored in a walk-in refrigerator (<4°C). Samples were analyzed for explosive content and heavy metals by methods outlined in the EPA Solid Waste Analytical Manual SW-846 Version 2 as follows: explosives by immunoassay (EPA Methods 4050 and 4051), explosives by HPLC (EPA Method 8330), and heavy metals by microwave digestion (EPA Method 3051) followed by ICP-MS (EPA Method 200.8). Due to positive interferences encountered with arsenic analysis in seawater, As was determined by Hydride AA (EPA Method 7061).

Samples for analysis of explosive compounds were screened by immunoassay for TNT and RDX. Samples that tested positive by immunoassay were then confirmed by HPLC. Reference sand purchased from a local Home Depot (Athens, GA) was used to create sediment trip blanks and used for MDL and fortified sediment recovery studies.

To evaluate the health-risks associated with the heavy metals and explosives found in the seawater samples, our residue levels were compared with the EPA Drinking Water Standard.[1]Fish and lobster residue levels for all metals except arsenic were compared to the RBC Guidelines.[1]The risk level used for the assessment was 1/1,000,000. Since there is disagreement over arsenic screening levels, an initial value of 0.026 ppm for total As was used.[2]This value was adjusted by a factor of 5 and 10 for lobsters and fish. This was done to account for the observation that only 20% and 10% of the total As in lobsters and fish, respectively, is in the toxic inorganic form. Concentrations of explosives were compared to values found in the RBC Guidelines.[3]

Results

Ecological Survey

Evidence for military activity is everywhere within the bombing range. Viequean coral reefs are littered with unexploded ordnance and bomb casements. This underwater unexploded ordnance (UWUXO) has resulted from the intense bombing (Fig.2[top]) and shelling (Fig.2[bottom]) to which this area has been subjected over the past 60 years. Table4lists the density of ordnance within the belt-transects. This ordnance included rifle and small-arms munitions and casings, a 500-pound air-dropped bottom-mine, a 2.75″ rocket, air-dropped high-speed, low drag bombs (and their associated "snake-eye" fin assemblies), dispensed munitions canisters, air-dropped flares (with parachutes still attached), and a 500-pound bomb. Two-thousand pound GP (General Purpose) old-style bombs also occur on the reef, especially south of Roca Alcatraz (Figs.1and4[upper left]). During storms, almost all of these munitions, and definitely any dispensed munitions or aerial flares with parachutes attached, move around the reef striking sea fans, corals, and other benthic organisms.

Table 4

The relationship between coral reef health and the density of military ordnance at several coral reef locations, Isla de Vieques, Puerto Rico (Fig.1[bottom])

Vieques locations	**Bahia Salina del Sur Map station 1 18° 07′ 50.30″ N; 065° 18′ 2.40″ W**		**Roca Alcatraz Map station 3 18° 07′ 35.90″ N; 065° 18′ 4.01″ W**		**Ensenada Honda Map station 4 18° 06′ 48.50″ N; 065° 21′ 37.70″ W**	
	Station A	**Station B**	**Station A**	**Station B**	**Station A**	**Station B**
	6.0 m	**6.0 m**	**7.0 m**	**6.5 m**	**6.2 m**	**6.0 m**
Ordnance/m^2	0.25	0.28	0.08	0.13	0.00	0.00
Colonies/m^2	1.15	1.18	1.48	1.68	3.15	2.73
Species number (S)	8	6	12	9	23	22
(S/m^2)	0.20	0.15	0.33	0.23	0.58	0.55
Species richness (Margelef Index)	1.83	1.30	2.70	1.90	4.55	4.48
Species diversity Shannon index (H′)	1.42	1.42	2.16	1.95	2.30	2.23
Species evenness Shannon index (E)	0.52	0.69	0.72	0.78	0.44	0.42
Gorgonia ventilina	3 (All diseased[a])	4	3 (No disease)	3	8 (No disease)	15
Fire coral/m^2	1.03	0.60	0.05	0.08	0.13	0.15
Urchins/m^2	0.85	1.25	0.18	0.28	0.05	0.03

Each Station is 40 m^2

[a]All*Gorgonia ventilina*colonies at Bahia Salina del Sur exhibited signs of aspergillosis fungal infections

Belt transects revealed that coral reefs seaward of Ensenada Honda (Site 4; Fig.1[bottom]) have 22 and 23 scleractinian coral species/40 m^2(Table4). By comparison, Carysfort, Rock Key, and Sand Key Reefs in the Florida Keys National Marine Sanctuary have only 11, 15, and 19 coral species, respectively [70], making the coral reefs of Vieques one of the richest and most bio-diverse of all new world coral reefs under US protection.

By comparing the density of military ordnance with standard metrics of coral community structure (Table4), the data allow us to plot the effect of increasing military activity on coral reef ecosystem health (Fig.6). Linear regression models for ordnance density versus colony abundance, species richness, and coral species diversity all give significant negative correlations ($p = 0.02$, $r^2 = 0.77$; $p = 0.007$, $r^2 = 0.86$; and $p = 0.0005$, $r^2 = 0.96$, respectively), demonstrating an inverse relationship between military activity and all standard measures of coral reef health. Regardless of which parameter is chosen, coral reef vitality decreases as military activity increases. Conversely, coral reef health increases as the distance from the center of the bombing range increases.

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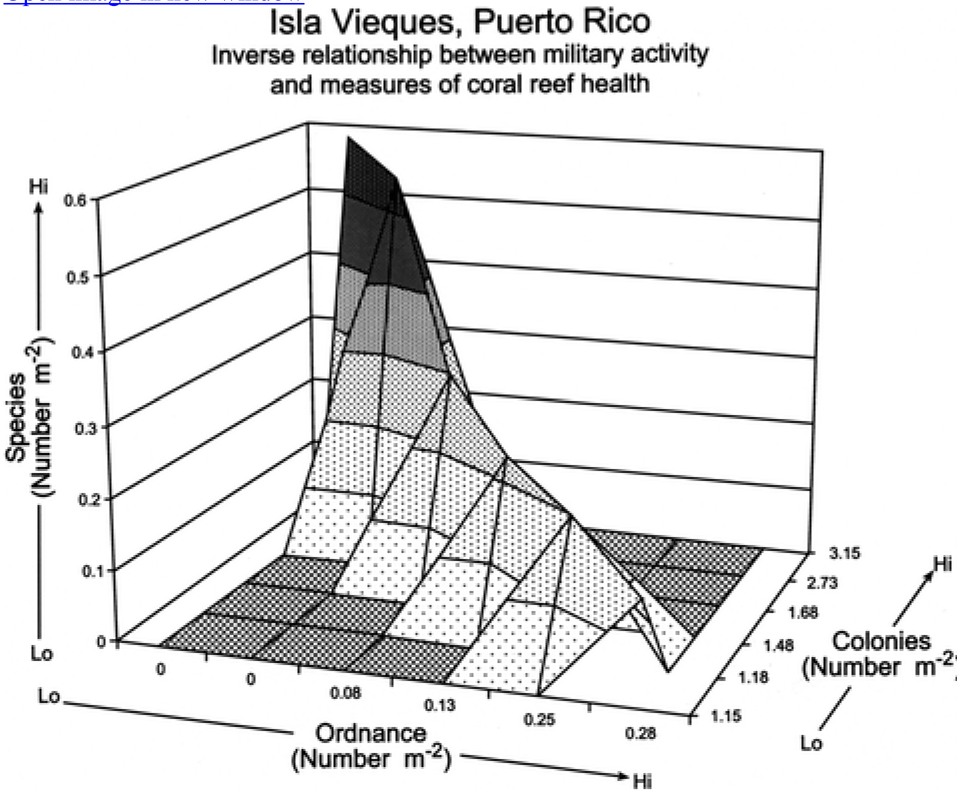

Fig. 6

Three-dimensional relationship between the density of military ordnance (number of objects per m^2), coral colony density (colonies per m^2), and coral species richness (species per m^2). All measures of coral reef health decline with increasing military activity

The opposite trend holds for the relationship between ordnance density and either fire coral abundance (number of *Millepora alcicornis* colonies per m^2) or sea urchin abundance (number of *Diadema antillarum* individuals per m^2) (Table 4). Linear regression produces a positive relationship for both fire coral density ($p = 0.06$; $r^2 = 0.63$) and sea urchin density ($p = 0.003$; $r^2 = 0.92$).

All sea fans (*Gorgonia ventilina*) within the bombing range site at Bahia Salina del Sur were infected with the fungal disease, *Aspergillus sydowii*, whereas none of the sea fans in transects outside the bombing range at Ensenada Honda were infected (Table 4). Small sample sizes prevent statistical treatment of these observations.

Magnetometer Survey

Figure 7 shows that metallic shrapnel was detected in almost every quadrant of the impact crater's wall. A majority of the metal in the detonation debris field is embedded in the southeastern and northwestern quadrants of the crater. The distribution of shrapnel is consistent with south to north bombing runs over the Viequean bombing range (Fig. 1 [bottom]). Figure 7 also reveals small, but reliably measured, lateral blowout debris fields. Although invisible to the naked eye, the presence of metallic items embedded within the reef is revealed by the metal detector (Fig. 5).

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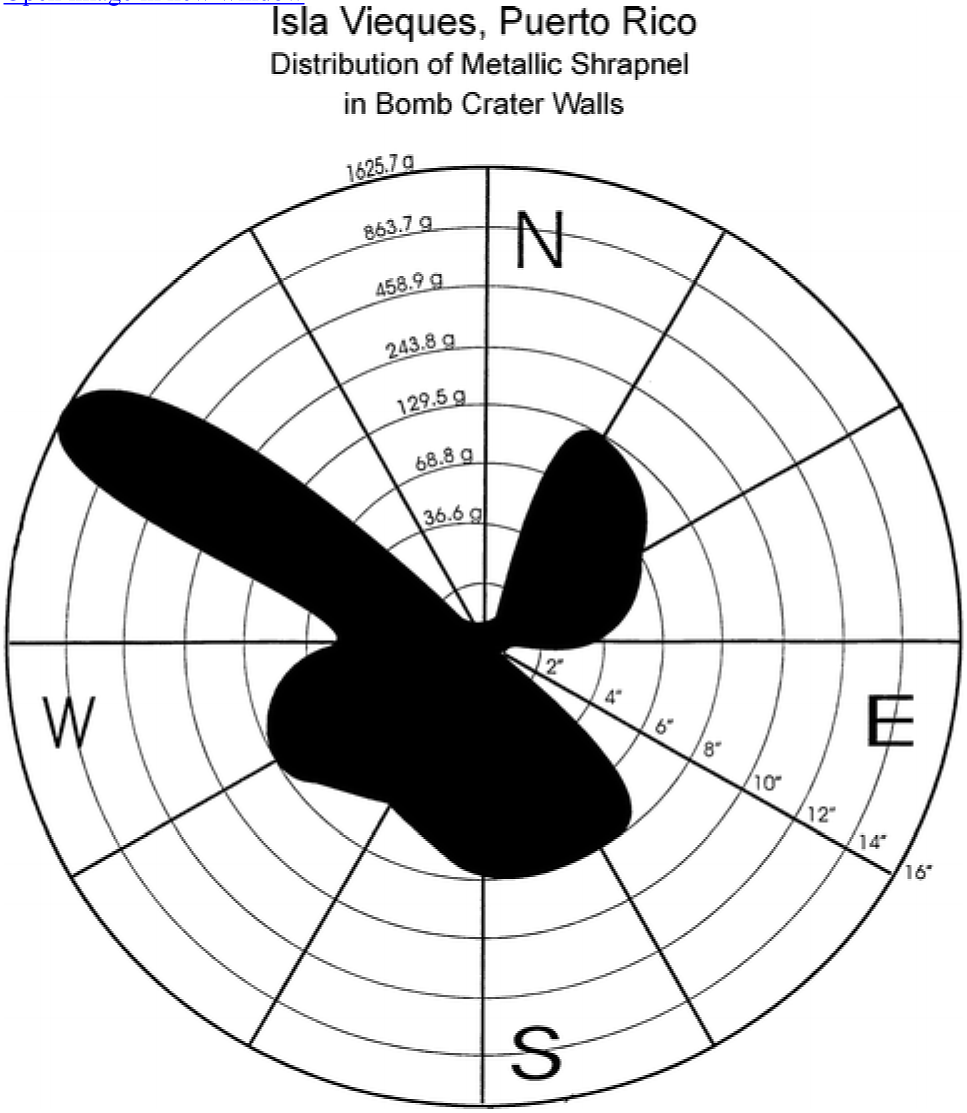

Fig. 7

Polar-coordinates graph of the distribution of minimal mass (see Methods Section) of metallic shrapnel from the bomb crater shown in Fig.4[upper right]. Shrapnel was detected in almost every quadrant of the crater's wall. This diagram demonstrates that a majority of the metallic objects imbedded in the reef are lodged in southeastern and northwestern crater walls, consistent with south to north bombing runs (see Fig.1[bottom])

Radiological Status of the Site

Underwater gamma spectra for all measured locations were at background levels and well below any level that would cause human health risks (Fig.8). No peaks were detected in any of the spectra, indicating the absence of man-made radiological contamination. Fission products associated with radioactive fallout from nuclear testing were absent from all samples.

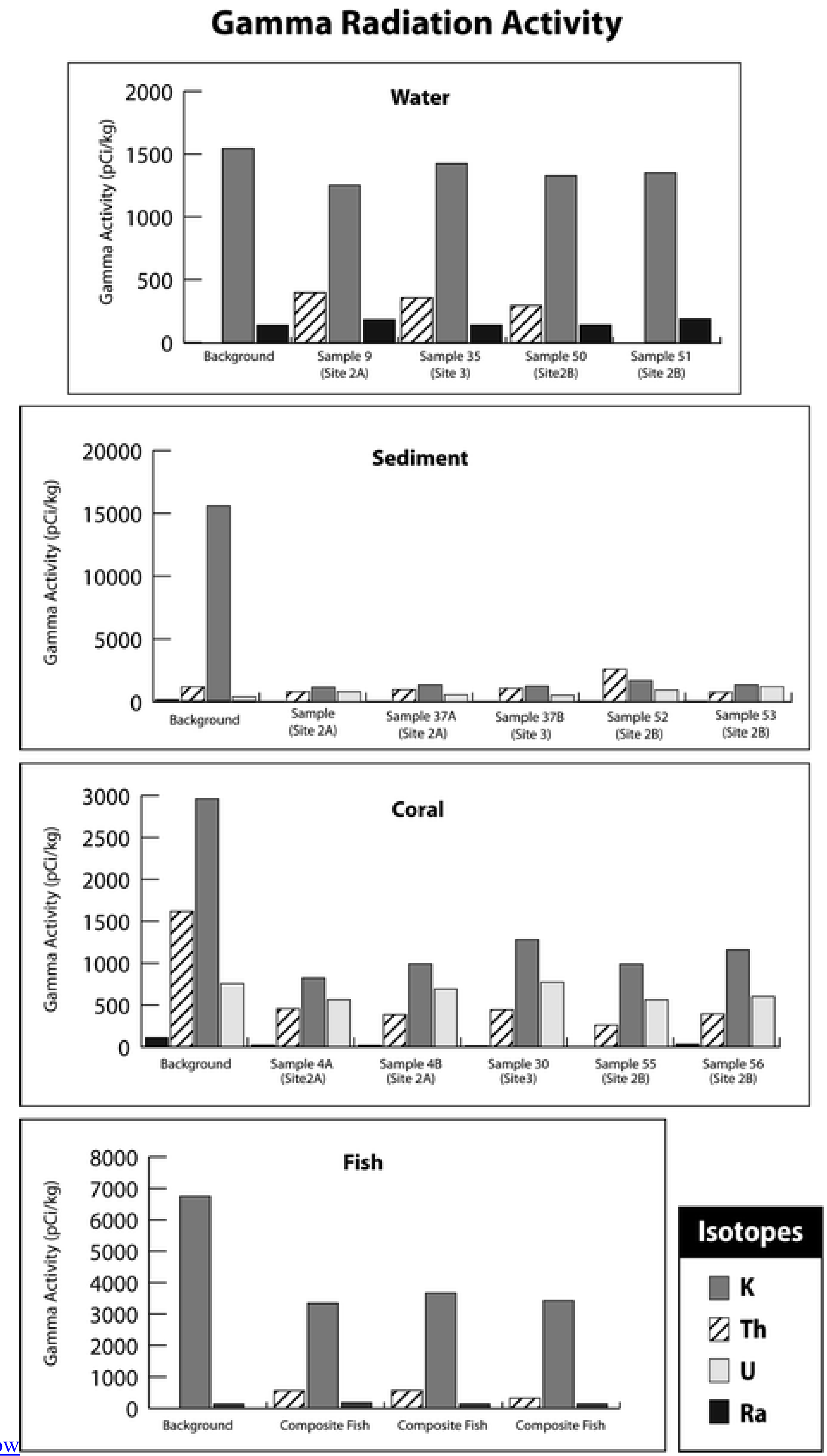

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Fig. 8

Gamma radiation activity of water, sediment, coral, and fish from marine habitats near the wreck of the USN*Killen*and Roca Alcatraz on the eastern end of Isla de Vieques, Puerto Rico

Water samples had very little gamma activity (Fig.8). Water samples were all below the detection limit for ^{238}U. Average seawater contains approximately 1 pCi/kg, which is considerably below the minimum detection capability (18 pCi/kg) for our HPGe gamma detection protocol [48]. Ratios for U/Th, Th/K, and U/K could not be calculated due to the absence of ^{238}U and ^{232}Th.

Measured gamma activity detected in the marine sediment samples (Fig.8) are primary radionuclides [78] and are naturally present in marine sediments [uranium (^{238}U), thorium (^{232}Th), potassium (^{40}K), and radium (^{226}Ra)]. ^{238}U reflects the uranium content of phosphatic deposits often found in tropical coastal regions, ^{232}Th is associated with carbonate mineral deposits, and ^{40}K is often found in fine-grained clay sediments [44]. ^{226}Ra is a long half-life decay daughter of uranium and is commonly found in marine sediment [78]. U/Th, Th/K, and U/K ratios were consistent for all samples, indicating a natural distribution of isotopic composition in sediments from Bahia Salina del Sur and Roca Alcatraz.

The sediment background sample (Fig.8) was collected offshore in Hatillo, located along the northern shore of mainland Puerto Rico. While ^{238}U and ^{232}Th gamma activities from Hatillo were very similar to those measured on Vieques, ^{40}K activity was considerably higher (Fig.8) from the mainland sample. This was most likely due to higher clay content in the background sample from Hatillo.

Gamma activities in coral (*Diploria labyrinthiformis*) from all three sites were normal (Fig.8). The background coral sample collected offshore Hatillo, Puerto Rico, had slightly higher gamma activities for ^{238}U, ^{232}Th, ^{40}K, and ^{226}Ra than did coral from Bahia Salina del Sur (Fig.8). However, the U/Th, Th/K, and U/K ratios were nearly identical from all locations, indicating a natural isotopic distribution.

A metal sample was collected from the underside of corals growing on the deck plates of the USN*Killen*(Fig.3[top and bottom]). When coral was removed from the USN*Killen*, a layer of metal adhered to the coral head. The metal from the USN*Killen*'s hull was scraped from the corals and packed for analyses. The metal sample from the vessel was the final sample needed to associate or disassociate the USN*Killen*with any form of radioactive contamination that may have occurred during the*Killen*'s role in atomic bomb blasts in the Pacific Ocean in 1958. None of the fission products associated with nuclear bomb testing were detected.

Composite fish samples were also tested for radioactivity (Fig.8). No ^{238}U was present in the composite fish samples. The ^{40}K, the isotope with the highest gamma activity in the composite fish samples, is typically present in living tissue [80]. U/Th and U/K ratios could not be calculated due to the absence of uranium. The background fish (Fig.8) was salmon bought locally in Athens, Georgia. ^{226}Ra levels were similar in both the salmon and the Viequean fish, but the salmon had higher ^{40}K and lower ^{232}Th gamma activities than the fish from Bahia Salina del Sur (Fig.8). These slight differences could have come from the origin of the fish and the environment in which they lived.

Chemical Contamination

Bahia Salina Del Sur

Water and sediment around the USN*Killen*wreck site in Bahia Salina del Sur were generally free of chemical contamination (Table2). For instance, water samples collected from the three USN*Killen*sites sampled contained no detectable TNT (<5 ppb) or RDX (<5 ppb) by immunoassay or HPLC (Table2). One water sample from the USN*Killen*bow contained a positive indication of RDX by immunoassay, but this observation could not be confirmed by HPLC analysis. Likewise, sediment samples from these three USN*Killen*sites contained no detectable TNT or RDX by immunoassay (<0.5 mg/kg TNT and RDX) or HPLC (<1.2–1.3 mg/kg TNT and RDX) (Table2). One sediment sample from near the USN*Killen*bow section showed trace quantities (0.5–1.5 mg/kg) of TNT by immunoassay, but this finding could not be confirmed by HPLC (<1.2 mg/kg) (Table2).

There was no heavy metal contamination in either water or sediments at Bahia Salina del Sur (Table2). Seawater samples from near the bottom of the water column were analyzed for arsenic (As), lead (Pb), and mercury (Hg) (Table2), barium (Ba), selenium (Se), cadmium (Cd), chromium (Cr), silver (Ag), and uranium (U). These elements were found in concentrations less than EPA's Risk-Based Concentration (<1 in a million risk of cancer or health impact) and EPA Drinking Water Maximum Contaminant Levels.

Explosive compound residue and heavy metal concentrations were also generally low in biological materials from all of the USN*Killen*sampling sites (Table2). Only one of the six coral samples collected from the USN*Killen*(stern section) contained detectable residues of TNT or RDX (Table2). The coral sample from this location contained 252 mg/kg TNT. Given the low levels of TNT found in the surrounding water and sediments at this location (Table2), the origin of this explosive residue is unknown. All other coral samples contained no detectable TNT (<1.2 mg/kg) or RDX (<1.3 mg/kg).

The fish composite samples from the USN*Killen*bow section contained no detectable TNT residues by either immunoassay (<0.5 mg/kg) or HPLC (<1.2 mg/kg). A French Grunt sample from the USN*Killen*Stern section also contained no detectable TNT or RDX by immunoassay (<0.5 mg/kg) or HPLC (<1.2 mg/kg). One of the two duplicate fish composite samples from Site 1, however, gave a positive response for RDX in the immunoassay determination, but this could not be confirmed by HPLC.

The lobster composite (N = 3) from Site 1 contained no detectable TNT (<1.2 mg/kg) or RDX (<1.3 mg/kg).

In general, the elements Ba, Cd, Cr, Se, and Ag were well below the EPA Risk Based Concentration Guidelines for composite fish samples from*Killen*Sites 1 and 2. The sample size and dilutions used in the analysis precluded obtaining detection limits at or below the EPA Risk Based Contaminant Level for U and Hg. A Risk-Based Concentration for Pb was not listed, but a health effect level of 0.3 mg/kg is commonly accepted [7]. No gross contamination with U, Hg or Pb was indicated for fish (Table2), but a lead contamination level of 8.14 mg/kg for the coral sample from this site (Table2) suggests further sampling is warranted. Elemental levels for Ba, Cd, Cr, Se, Ag, Hg, Pb and As in fish are also within the safe ranges reported for Vieques by CDC and the ATSDR [7].

Arsenic is a problem at both Sites 1 and 2 in Bahia Salina del Sur. The concentration of arsenic in fish from these two sites (0.77 and 1.05 mg/kg, respectively) is twice EPA's allowable level (0.26 mg/kg). In addition, lobster from Site 1 (38.4 mg/kg) has more than 300 times EPA's allowable (fish) level of 0.16 mg/kg.

Roca Alcatraz

Everything in and around the submerged bomb was contaminated (and in some instances highly contaminated) by explosive compounds and explosive residues (Table3). Water at the bombsite contained seven known carcinogens: (1) 1,3,5-Trinitrobenzene; (2) 1,3-Dinitrobenzene; (3) 2,4,6-Trinitrotoluene; (4) 2,4-Dinitrotoluene + 2,6-Dinitrotoluene; (5) 4-Nitrotoluene; (6) 2-Nitrotoluene; and (7) Hexahydro-1,3,5-Trinitro-1,3,5-Triazine. Seawater at the bomb's surface exceeded safety standards for every compound detected, including 1,3,5-Trinitrobenzene (11,525 ppb); 1,3-Dinitrobenzene (18,500 ppb); 2,4,6-Trinitrotoluene (85,700 ppb); 2,4-Dinitrotoluene + 2,6-Dinitrotoluene (82,500 ppb); 2-Nitrotoluene (40,500 ppb); and Hexahydro-1,3,5-Trinitro-1,3,5-Triazine (4,120 ppb) (Table3).

Replicate seawater samples collected a centimeter away from the bomb contained 17.7 ppb and 7.9 ppb TNT, respectively. These values are well above the EPA Risk Based Concentration guideline of 2.2 ppb. Water samples collected 10 cm away from the bomb had generally lower concentrations: 8.15–14.9 mg/kg of 1,3,5-Trinitrobenzene; 13.6–23.4 mg/kg of 1,3 Dinitrobenzene; 66.4–105 mg/kg of TNT; 58–107 mg/kg 2,4-Dinitrotoluene + 2,6-Dinitrotoluene; 26.4–54.6 mg/kg of 2-nitrotoluene; and 3.28–4.96 mg/kg of RDX (Table3).

Sediment samples also showed exceedingly high concentrations of many of these same compounds. Sediments physically adjacent to the bombsite had high levels of 1,3,5-Trinitrobenzene (30.7 mg/kg); 1,3-Dinitrobenzene (3.47 mg/kg); 2,4,6-Trinitrotoluene (19,333 mg/kg); 2,4-Dinitrotoluene + 2,6-Dinitrotoluene (26.0 mg/kg); 4-Nitrotoluene (5.39 mg/kg); and Hexahydro-1,3,5-Trinitro-1,3,5-Triazine (5.32 mg/kg). Sediments farther away had concentrations of TNT of 4,380 mg/kg at 0.01 m, 506 mg/kg at 0.10 m, 354 mg/kg at 1.0 m, and 0.0 (non-detection) at 2.0 m. Chromium concentrations in sediment follow a similar rapid decline, with values of 6.87, 2.27, 1.59, and 1.96 mg/kg at distances of 0.0, 0.01, 1.0 and 2.0 m, respectively.

Exponential Decay of Toxic Substance Concentrations

Despite the limited number of samples taken, several trends emerge from these spatially explicit data on water and sediments. The concentration of toxic substances dissipates rapidly as the distance from the bomb increases (Table3; Fig.9). For chromium in sediments and for TNT in both water and sediments, there appears to be an exponential decline with increasing distance from the UXO (Fig.9).

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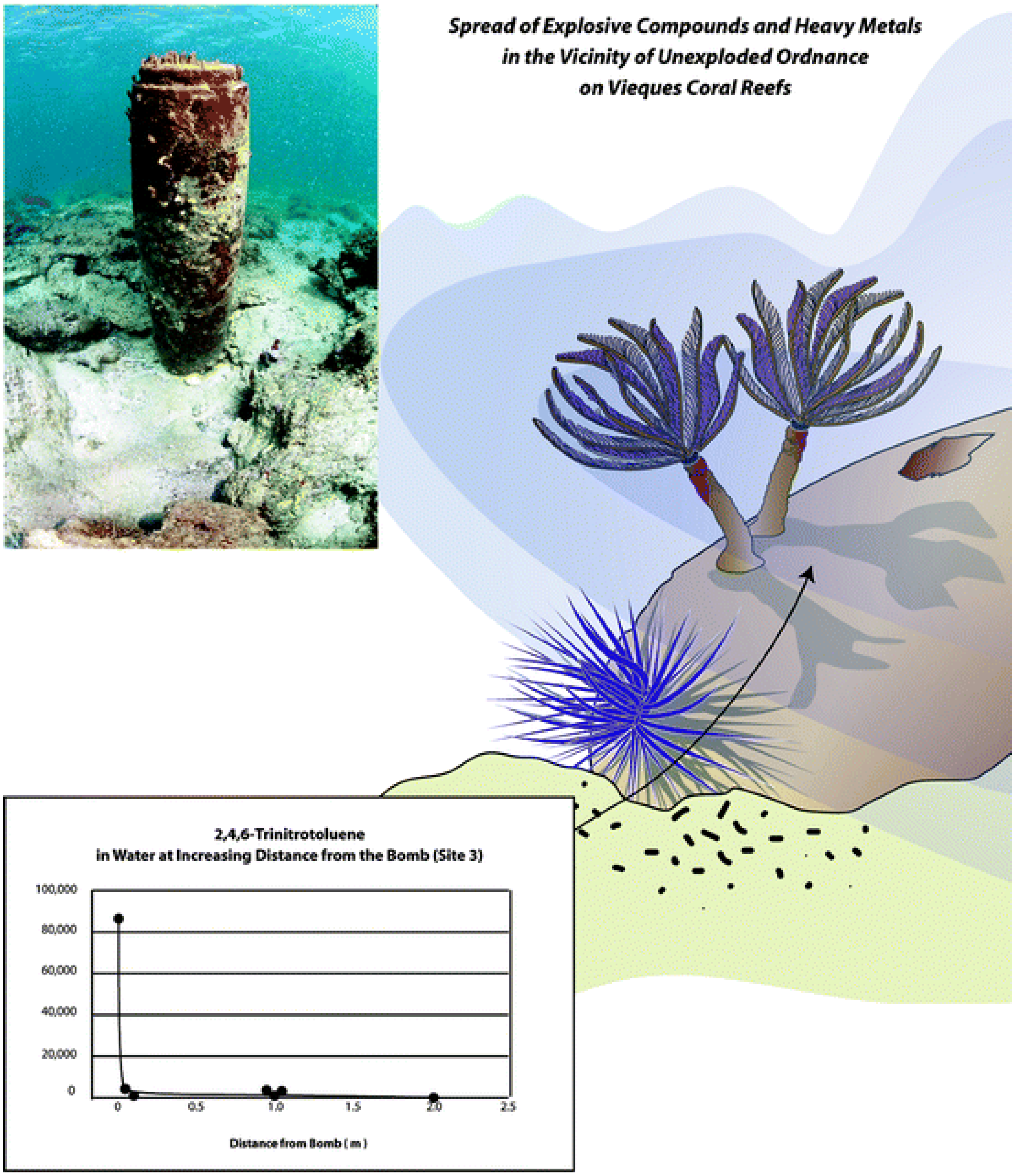

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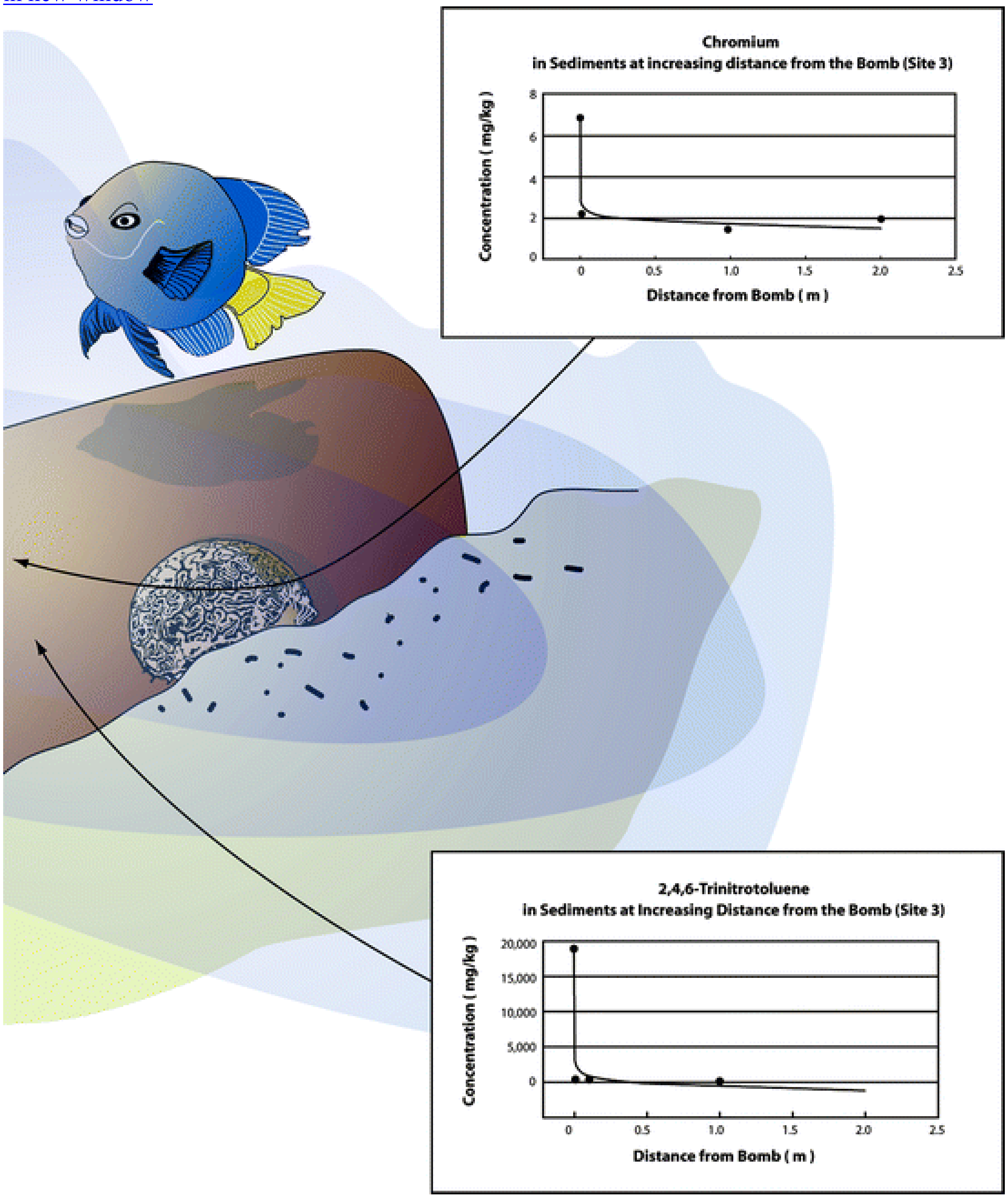
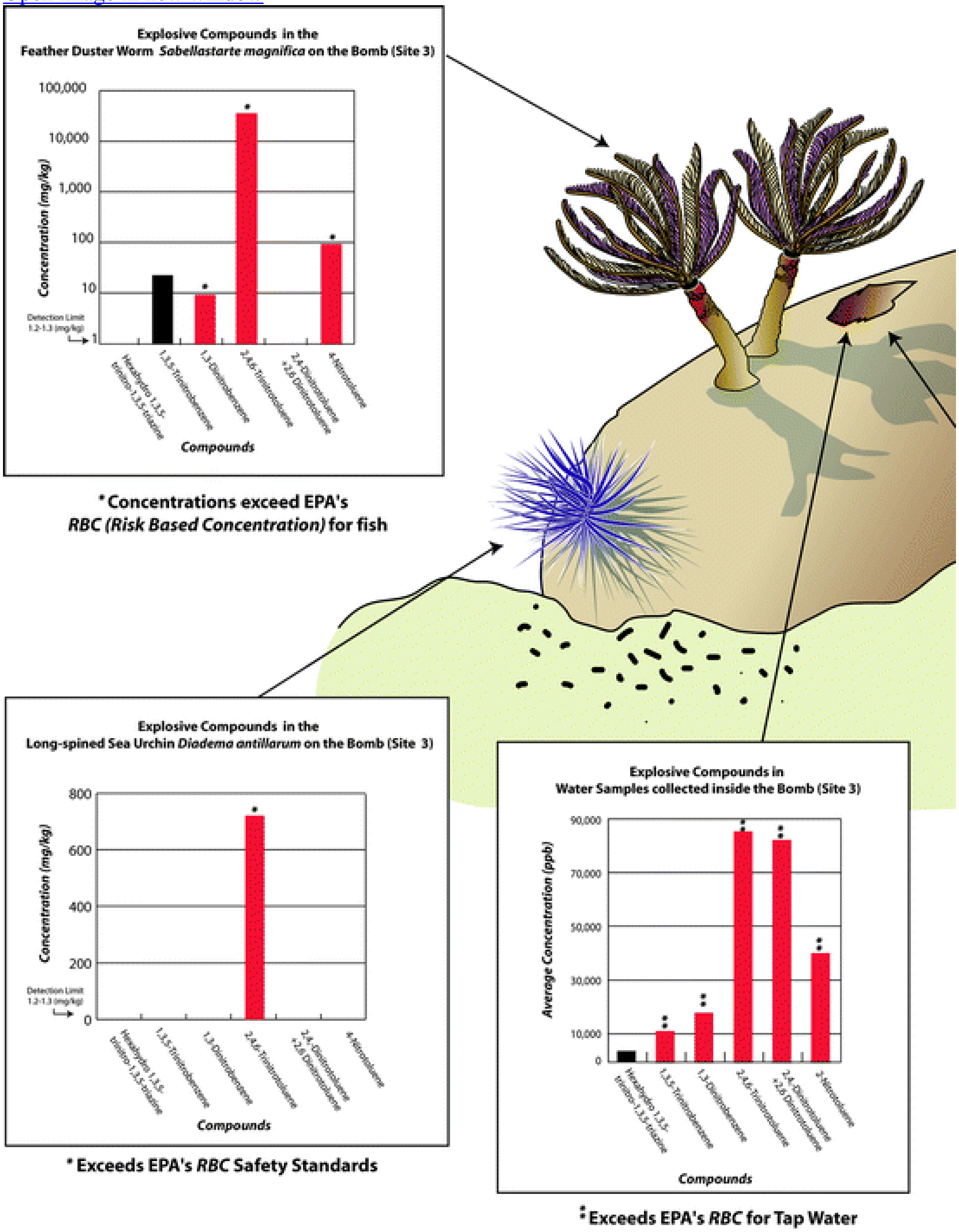


Fig. 9

Spread of explosive compounds and heavy metals in the vicinity of unexploded ordnance on Vieques coral reefs. The concentration of explosive materials and heavy metals in sediment falls off exponentially as a function of increasing distance from the bomb

Living organisms at the site are highly contaminated with these toxic compounds (Table3; Fig.10). The star coral in physical proximity to the bomb exhibited extreme signs of stress including loss of symbiotic algae and reduced chlorophyll content (Fig.4[lower right]). This colony had TNT concentrations of 600 mg/kg, as well as high concentrations (250 mg/kg) of 1,3,5-Trinitrobenzene, 1,3-Dinitrobenzene, and 2,4-Dinitrotoluene +2,6-Dinitrotoluene (Table3).

Open image in new window



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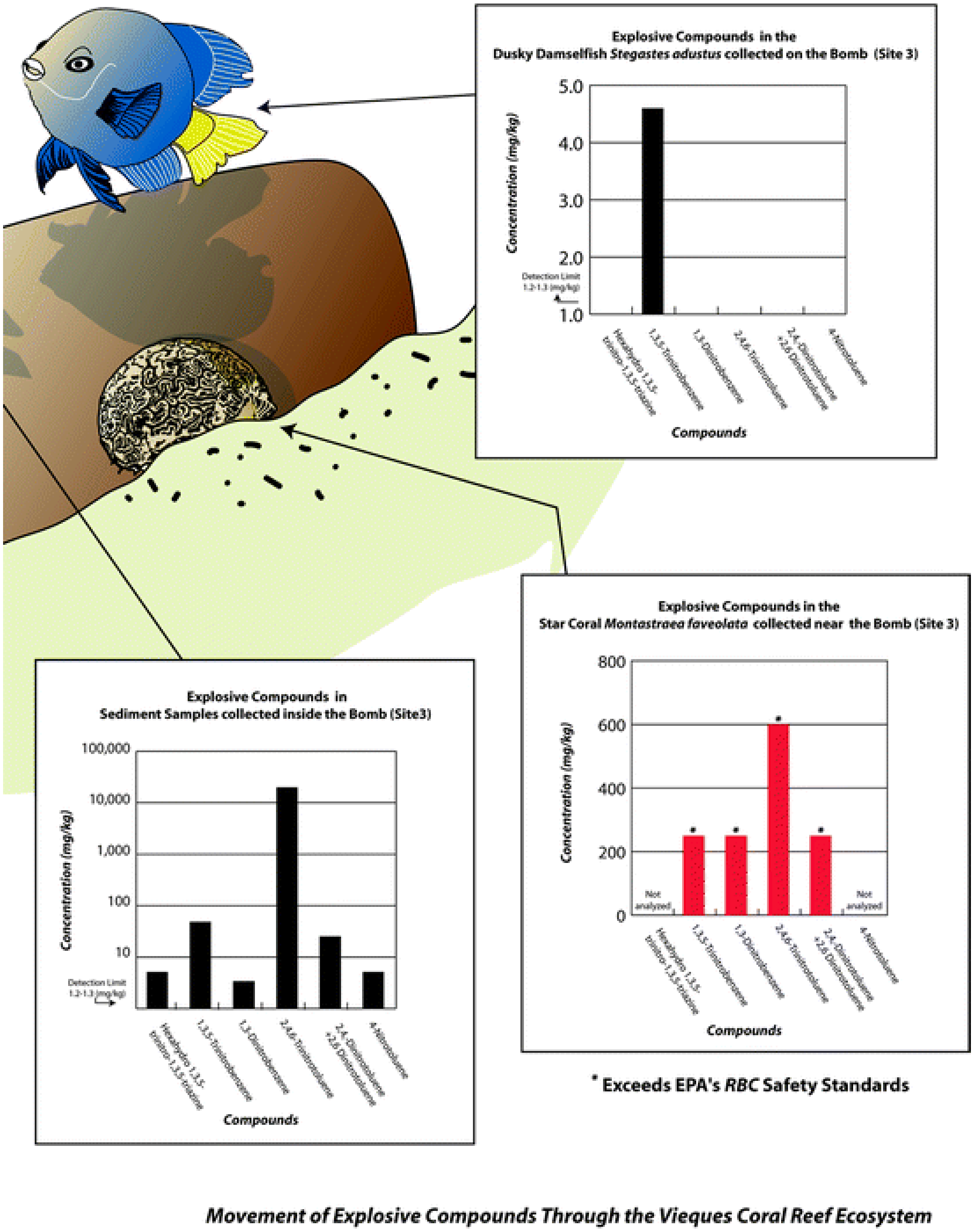

Fig. 10

Movement of explosive compounds through the Vieques coral reef ecosystem. Explosive and toxic materials exist in the environment and all biota tested from near a 2,000 lb General Purpose air-dropped bomb at Isla de Vieques, Puerto Rico (Site 3), including water, sediment, feather duster worms, sea urchins, coral, and fish. A single asterisk indicates that the concentration of that material exceeds EPA's Risk-Based Carcinogenic Concentration guidelines for edible seafood; a double asterisk indicates that the values exceed EPA's safe drinking water standards

Other aquatic organisms, which were attached to or adjacent to the bomb, contained significant quantities of TNT, for instance the feather duster worm (40,200 mg/kg TNT) and the sea urchin (721 mg/kg TNT) (Table3; Fig.10).

The damselfish collected at the bombsite contained no detectable TNT or RDX by immunoassay (<0.5 mg/kg) or HPLC (<1.2 mg/kg, <1.3 mg/kg, respectively), but did contain trace levels of 1,3,5-Trinitrobenzene (4.6 mg/kg).

Discussion

Scientific Findings

Ecological Conditions

The spatial and temporal scales of one's survey techniques determine one's ability to detect the impact of military activity on Vieques coral reefs. Surveys which average data collected over great expanses of coastline reveal nothing [72]; surveys which emphasize small-scale studies reveal widespread damage [66,67,73].

In 2009, the US Navy provided the Centers for Disease Control in Atlanta [9] with a summary of the live-ordnance water hits (including air-dropped bombs and naval gunnery artillery shells) that took place during the period from 1989 to 1999 (e-mail message from David F. McConaughy to Rita Tallini, June 18, 2009). The Navy stated that 881 water strikes occurred during that time period. The commonest round to hit the water was a 5–54 projectile. Localized damage to the fore reef in the LIA includes massive cratering (Figs.4[upper right] and 5), broken coral, sunken vessels (Fig.3[top and bottom]), and a seafloor littered with UXO (Fig.4[upper left]), high explosives (Figs.4[lower left] and 10), illumination flares, laser-guided bomb fin assemblies, machine gun bullets, 18 in. artillery shells, compressed gas cylinders, 55-gallon drums, 4–5 in. mortars, and parachute flares. Geomarine [32] estimated that 1,722 $m^2$of coral reef had been hit by live ordnance and that 31,696 $m^2$of sea grass had also been hit. Every author that has worked in the LIA has reported this kind of localized damage [4,26,32,39,66,67,72,73].

Our ecological surveys were conducted on a small scale (with transect areas averaging 40 m^2) and were specifically designed to include a range of environmental impacts on fore-reef sites both inside (Fig.1[bottom]; Site 2) and outside (Fig.1[bottom]; Site 4) the LIA. These surveys demonstrate a clear inverse relationship between military activity and coral reef health (Table4; Fig.6). Our data also show that as one moves away from Bahia Salina del Sur, the impact of military activity falls off rapidly. If this pattern of rapid decline in impact is confirmed by further sampling, it means that a majority of the reefs around the island of Vieques are probably relatively free of the mechanical damage that is so prominent in and around Bahia Salina del Sur.

The density of live-air-dropped bombs on the eastern end of Vieques is shown prior to 1980 in Fig.2[top]. This map expresses the data in terms of live bombs/acre/year in the zones of highest impact, but does not include information on less frequent, but environmentally important, misses in which bombs fall in near shore sea grass beds and on offshore coral reefs. The large number of these bombs littering the sea floor in this region (Fig.4[upper left]) suggests that these occurrences are much commoner than this ordnance density overlay suggests. Finally, this map also does not show any of the historical bombing targets, such as the USN*Killen*, which were targeted while they were floating over the reef. A substantial proportion of bombs and projectiles dropped on or aimed at this target would have fallen onto the coral reef.

The density of impacts of naval gunfire on land-based targets is shown in Fig.2[bottom]. As in Fig.2[top], the map expresses the data in terms of rounds/acre/year. This map demonstrates that rounds from naval gunfire did enter the water offshore from their land-based targets, but does not show the density of less frequent misses in which artillery shells fell far from the mark and landed in sea grass beds and on coral reefs. The prevalence of "errant" munitions on the reef proves that it was impossible, under combat simulation, to guarantee that bombs aimed at the land would never fall on the reef.

In their review on the use of statistics in environmental surveys, Brosi and Biber [20] point out a crucial distinction between Type I and Type II statistical errors. Type I errors (saying that a difference exists when, in fact, it does not) are quite rare in the published literature. However, Type II errors (saying that no difference exists when either it does, or there is no proof that it does not) are quite common. Ecologists often assume that they are being "rigorous" if they assert that two populations are identical ("the null hypothesis"), and then statistically test to identify differences between them. If a significant difference is not found, they then accept the null hypothesis as true: that there is no difference between the two populations. This is, in fact, a Type II statistical error because they have not proven that the two populations are the same, only that the null hypothesis cannot be rejected. We do not know whether or not the two areas being compared are the same or not; you know only that we cannot reject the null hypothesis. Hoenig and Heisey [41] and Lemons et al. [47] point out that this mistake is especially pernicious in environmental and conservation contexts because it leads to the false assertion of "no harm" or "no effect," when this is in fact, not known.

Surveys on Vieques are replete with Type II errors. For instance, in comparing Vieques and St. Croix coral reefs, Riegl et al. [72] state, "Diversity statistics based on *in situ* coral counts showed no differences between inside and outside the bombing range, confirmed by Mann–Whitney U-tests. Also, data of transects pooled per site suggest no difference.…The most pronounced outcome of this study was the lack of differentiation within and between the coral communities of Vieques and St. Croix." With the null hypothesis rejected (that there has been no effect of military activity on Viequean coral reefs), Riegl et al. [72] then speculate that, "The effects of natural disturbances were severe at Vieques, outweighing impacts of past military activity–which were present but not quantitatively discernible at our scale of sampling. Germs and storms, rather than bombs (and associated naval activities), primarily seem to have taken the worst toll on corals at both Vieques and St. Croix." And further that, "At Vieques, the *Acropora palmata* zone was almost completely lost, and it was severely reduced at St. Croix, presumably primarily due to diseases and hurricane impacts since the 1970s.…we found no differences in living benthic coral reef cover or composition of coral assemblages inside and outside the bombing range or in comparison to reefs investigated on St. Croix. This indicates not that zero impacts occurred but rather that natural disturbances appear to have altered the coral communities drastically, thus obscuring military impacts."

We accept that broad scale surveys conducted in St. Croix and on Vieques are unlikely to show any differences between these two locations. We also agree that both hurricanes and disease are powerful drivers of coral reef survival in the Caribbean. However, we assert that the St. Croix/Vieques comparisons provided are irrelevant to the question of whether or not military activity has impacted the Viequean coral reef. From a statistical perspective, if these comparisons are used to suggest that there has been no effect of more than 60 years of naval bombardment on the Vieques coral reef, we also assert that this suggestion is unsupported by the statistical tests applied.

An alternative way to pursue the question of the effect of naval bombardment on the Viequean coral reef might be to examine craters on the reef (Fig. 5) and attempt to back calculate coral survivorship as a function of coral morphology and distance from bomb blasts (see Fig. 7). Given the friable nature of endangered species within the family *Acroporidae*, we predict that the detonation of a 2,000-pound bomb (Fig. 4[upper left]) in the aqueous environment of a coral reef will be highly lethal over an extremely large area. We concur with Riegl et al.'s observation [72] that, on Vieques, "Only skeletons, stumps, and rubble were still abundant. Unless live, as well as dead, corals were taken into account, the classical Caribbean shallow *Acropora palmata* zone [36] was barely visible."

Through satellite mapping, Hernandez-Cruz et al. [39] documented the loss of *A. palmata* between 1975 and 1985. Riegl et al. [72] interpret this decline as caused by regional-scale disturbances such as hurricanes and disease. While these influences are possible, what we know happened during that time period is that the Navy's departure from Culebra coincided with a massive increase in bombing on Vieques [86]. Therefore, we do not find it coincidental that "Antonius and Weiner [3] were the last to observe dense stands of living *A. palmata* in Bahia Salina del Sur and around Roca Alcatraz at Vieques." Nor that they observed in the mid-1970's that "*A. palmata* was by far the commonest coral in their study sites (more than 50% of all corals)" [72]. We hypothesize that with increasing bombing activity on Vieques at this time, populations of this endangered species and the surrounding coral reefs in the LIA were simply destroyed.

Radiation Safety

If any radioactive material were present in association with the wreck of the USN *Killen*, it would also be in the surrounding waters. Water samples had very little gamma activity (Fig. 8); all were well below the detection limit for ^{238}U.

Live brain coral samples (*Diploria labyrinthiformis*) were collected from each of the survey sites for gamma activity analyses. Coral collection was chosen in addition to marine sediment because of the potential that live coral could ingest small radioactive particles that could be present in or around the survey sites located in Bahia Salina del Sur. The ingested radioactivity would then become stored in the calcium carbonate coral skeleton [74]. No abnormal radioactivity was found in either sediments or coral formations analyzed (Fig. 8).

Larger biological organisms, such as fish, can also bioaccumulate radioactive particles during feeding which would be stored in their body. Reef fish, which included French angel, blue tang, French grunt, red hind, and yellowtail snapper, were collected near the two survey sites of the USN*Killen*. A total of eleven fish were collected at the two sites and the whole fish were processed as composite samples and packed in the Marinelli beakers. No radioactivity was present in the composite fish samples.

The contents of 55-gallon drums from the USN*Killen*were analyzed to explore the possibility that they may have contained radioactive material transported to the US from the mid-Pacific atomic bomb blasts for analysis in the US. The^{137}Cs gamma activity detected in the drums was at the minimum detectable level for the HPGe, indicating that^{137}Cs was present, but in very low activity levels. The calculated MDA for^{137}Cs is 10 pCi/kg with an uncertainty of 3 pCi/kg. However the peak identification for^{137}Cs in the drums was 99% positive giving a good indication that it was present. Even with back-calculating the 30-year half-life, the^{137}Cs gamma activity would have been initially low. This would indicate that the^{137}Cs in the drum sediment was most likely from atmospheric fallout between 1945 and 1972, and not from highly contaminated radioactive sediment. The drums without^{137}Cs may have been filled with subsurface terrestrial sediment that had not been exposed to aerial dust from nuclear fallout.

In summary, we found normal ambient radiological readings in and around the USN*Killen*and in its cargo of 55 gal drums. Our readings indicate that there is no radiological health threat associated with either Bahia Salina del Sur or its fore-reef ecosystem.

Hazardous Compounds

As part of ATSDR's Vieques Consultation [9], the agency requested "a complete listing with the amounts of every and all materials, weapons, bombs, experimental testing, pesticides, fuels, radiological, chemical and biological weapons that were used on the land, sea, or air above Vieques during the 62 years that the Navy or other armed forces (including foreign forces) used the island for training or weapons testing." The list supplied by the Navy included "over 200 chemicals associated with military munitions and their degradation and combustion products. Of these, 20 are of greatest concern due to their widespread use and potential environmental impact, including 2,4,6-Trinitrotoluene (TNT), 1,3-Dinitrobenzene, nitrobenzene, 2,4-dinitrotoluene, 3-nitrotoluene, HMX, 2,4-diamino-6-nitrotoluene, 4-nitrotoluene, RDX, 2,6-diamino-4-nitrotoluene, methylnitrite, perchlorate, nitroglycerine, PETN, 1,3,5-trinitrobenzene, and white phosphorous. This summary includes the ordnance used at the L.I.A., Surface Impact Area (S.I.A.), and Eastern Maneuver Area (E.M.A.). Small arms munitions as well as artillery rounds were also used in the E.M.A" [9]. Gonenaga [34] made the following comment in his review of Viequean coral reefs: "Large numbers of unexploded ordnance in these reefs limit their future utilization as fishing and/or tourist centers. We can barely hope that leaching substances from oxidizing and degenerating ordinance do not pollute marine life in these areas." This is, in fact, occurring (Figs.4,9, and10).

In our surveys, we found seven explosive compounds leaching from (UWUXO), some of them in extremely high concentrations (Table3). These compounds include: 1,3,5-Trinitrobenzene; 1,3-Dinitrobenzene; 2,4,6-Trinitrotoluene; 2,4-Dinitrotoluene + 2,6-Dinitroroluene; 4-Nitrotoluene; 2-Nitrotoluene; and Hexahydro-1,3,5-Trinitro-1,3,5-Ttriazine. Although found in both the water and sediments surrounding UWUXO, these compounds have also been taken up by marine biota in this area (Table3; Figs.9and10). This material has been taken up by living organisms and is suffusing throughout the marine food web and the coral reef ecosystem. Every organism in close proximity to UWUXO contained at least one of these potentially toxic materials (Table3; Fig.10). In addition, concentrations of these substances in three non-commercial species (the feather duster worm, the sea urchin, and the coral) exceed EPA's Risk-Based Concentrations for commercially edible seafood (Table3; Fig.10). TNT was found in high concentrations in the feather duster worm (40,200 mg/kg), the mountainous star coral (600 mg/kg), and the sea urchin (721 mg/kg). The star coral had high concentrations of 1,3,5-Trinitrobenzene (250 mg/kg), 1,3-Dinitrobenzene (250 mg/kg), and 2,4-Dinitrotoluene + 2,6-Dinitrotoluene (250 mg/kg). In addition, the feather duster worm had unsafe levels of 1,3-Dinitrobenzene (9.5 mg/kg) and 4-Nitrotoluene (95.5 mg/kg) (Table3; Fig.10). Perhaps of greatest concern, 1,3,5 Trinitrobenzene was found in concentrations of 4.6 mg/kg in the dusky damselfish (Table3; Fig.10). Exceptionally high concentrations of these compounds were also found in both sediments and water surrounding UWUXO (Table3; Figs.9and10). Military ordnance is the only known source for any of these compounds.

Lower concentrations of several of these explosive compounds were also recorded from both living and non-living material inside Bahia Salina del Sur. While contamination levels here are considerably less in the bay than around

UWUXO off-shore of Roca Alcatraz (Table3), trace levels of RDX and TNT showed up by immunoassay in several samples of water, sediments, and fish from Bahia Salina del Sur. Even if these low level detections could not be confirmed by HPLC, the hazardous nature of these pollutants suggests that, at the very least, further testing is warranted.

The presence of TNT (252 mg/kg) in a coral growing on the stern deck of the USN*Killen*(Table3) is particularly worrisome. Even after close and repeated inspections of this area, we were unable to find any UWUXO. This demonstrates that hazardous materials occur even in biota that are not physically adjacent to UWUXO.

In 2001, ATSDR and USEPA collected 104 fish and 38 shellfish from six locations on Vieques, including the site we had sampled near the former USN*Killen*. Their samples included grouper, snapper, parrotfish, grunt, goatfish, and one honeycomb cowfish from the market. Based on their samples, they state, “Explosive compounds were not detected in any of the fish” [7]. In one of our two composite fish samples from Bahia Salina del Sur, however, we measured a positive response for RDX in the immunoassay, but this could not be confirmed by HPLC. In this particular instance, it is unclear if the disparity between our findings and those of the ATSDR can be explained by (a) low concentrations of the compounds involved or (b) differing detection thresholds in the techniques used. Alternatively, real differences might have been observed because we sampled different fish species or from slightly different places. Our finding of a damselfish from the fore reef with a body load of 4.6 mg/kg 1,3,5-Trinitrobenzene (Table2) lends weight to the possibility that concentrations of these high explosive compounds vary considerably from place to place, making the design of a fully comprehensive sampling design very difficult. For instance, if we assume that both our composite fish sample and the ATSDR’s sampling results are accurate, then it means that determining the safety of seafood from the LIA will require a more sophisticated and robust sampling design, one that captures the exceptionally high variation (as much as four orders of magnitude) from place to place and from fish to fish. However, this kind of a sampling design may be required to support the proposition [7] that, “It is safe to eat fish and shellfish from all of the areas sampled... even if people ate fish or shellfish solely from a single location (e.g., only from the fish market or only from areas around the L.I.A.).” Without knowing more about where the fish came from, we are not ready to embrace this sweeping conclusion.

In the above-mentioned study, ATSDR did find that, “metals were detected in the fish.” Our data on heavy metals ([14], Table2) are in agreement with both the types and amounts found in their fish samples.

Our data raise concerns about arsenic, lead, and mercury (Table2). Arsenic levels are above the EPA Risk Based Concentration Guidelines in both fish composites from these two sites (0.77 and 1.05 mg/kg, respectively; Table2). This is twice EPA’s allowable level (0.26 mg/kg). Further, the lobster sample contained arsenic concentrations of 38.4 mg/kg, almost 300 times the EPA Risk-Based Concentration Guideline for fish of 0.16 mg/kg. Although the FDA Guidance Document for As in shellfish states that 86 mg/kg may be acceptable, they report that the normal range for As in Atlantic Spinney Lobster is only 10–20 mg/kg. That puts the As level in the current study well above the normal range. The high arsenic levels found in lobster from the*Killen*site are also of special concern. Sunken ships and abandoned 55-gallon drums attract lobster (in the Florida Keys, 55-gallon drums on the sea floor are referred to as “lobster hotels”). Viequean fin and lobster fishermen preferentially seek out these structures and may be concentrating their food collection in these areas. ATSDR comments [7,9] that, “To be protective of all residents, ATSDR estimated exposure by determining the amount of metals people would most likely be exposed to over their lifetime if they ate fish or shellfish every day for 70 years. ATSDR then compared these levels to those that are considered to be safe by public health professionals. ATSDR found that it is safe to eat a variety of fish and shellfish from Vieques on a daily basis. However, due to the levels of arsenic found in lobster, people should limit their consumption of lobster to less than three times a week. ATSDR does not expect cancer health effects to occur in persons consuming up to two 8-ounce servings of lobster per week. This assessment is based on the assumption that all the arsenic was bioavailable” [9].

In contrast to ATSDR’s interpretation of the data, we make the following recommendation in reference to our preliminary sampling of fish and lobster from the USN*Killen*site: estimated exposures can exceed health guidelines (this statement is identical to ATSDR’s statement), and therefore, we recommend against eating fish and lobster from the USN*Killen*site until further testing establishes its safety (this statement is different from ATSDR’s recommendation). Our interpretation of these data is bolstered by expert testimony from Dr. William Sandoval (State of Georgia Toxicologist) who concludes [14] that, “seafood with this level of heavy metal contamination would be banned from sale in the State of Georgia.” He states further, “Waters that consistently produced fish or lobster with these heavy metal concentrations would be placed on a health advisory list.”

EPA sets the allowable lead levels in seafood at only 0.03 mg/kg. Our immunoassay detection capability for marine samples, however, is only <2.65 mg/kg, suggesting that further work on the lead content from fish and lobster from these sites is warranted. The 8.14 mg/kg lead contamination found in coral at Site 1 (Table2) adds weight to this recommendation and seems to corroborate Diaz and Massol-Deya's observations [25] demonstrating high lead concentrations in*Syringodium filiforme*(manatee grass) from Carrucho Beach, located at the southern section of the AFWTF and the potential for dispersion and bioaccumulation of heavy metals along the marine food chain.

Although the mercury concentrations we measured in fish (Table2) did not fall into a range that would currently trigger a health advisory, this may change as new, and much more stringent, exposure standards are adopted by the World Health Organization [57,61]. These authors showed that the mercury concentration in hair from women from Vieques of reproductive age is 8.96 ppm, compared to 1.0 ppm in women from Puerto Rico, and 1.4 ppm in women from the US. They conclude that women of reproductive age on Vieques were exposed to mercury concentrations that are unsafe for a developing fetus. Given high fish consumption by the residents of Vieques, it is natural to look at fish as a potential contributing source for these demonstrably high body burdens.

Point-Source Pollution

Despite the limited number of samples taken, several trends emerge from the data that may be used to guide further investigations. The concentration of toxic substances declines as the distance from the bomb increases (Fig.9; Table3). For chromium in sediments and for TNT in both water and sediments, there appears to be an exponential decline with increasing distance from the UXO (Fig.9). Since the concentration of explosive compounds is highest at the bomb, this suggests that picking up and removing UXO will have an immediate and beneficial effect on the reef by removing sources of toxic chemicals from the environment.

Two principles seem to be at play with the living biota of the reef that may determine the toxic content of biota within the bombing range: (a) proximity and (b) mobility. The closer an organism is to the bomb, the higher its concentration of toxic chemicals will be; the less mobile (and more sessile) an organism is, the higher its concentrations will be. As can be seen in Fig.9, water and sediments in the vicinity of the bomb have very high concentrations of explosive compounds. In the biota, the highest concentrations of these compounds occur in the feather duster worm, a sessile invertebrate living directly on top of the bomb (Fig.9). Moving slightly farther away, the coral growing adjacent to the bomb contains less TNT, but still a majority (4 of 6) of the explosive materials found in sediments and water from the bomb. The sea urchin is mobile and was found farther away from the bomb than either the feather duster worm or the coral, and perhaps not surprisingly, therefore has fewer toxic compounds and in lower concentration than found in either the worm or the coral. The more mobile and more distant damselfish has the lowest body load of explosive toxicants (4.6 mg/kg of 1,3,5-Trinitrobenzene). The brain coral located at 15 m from the bombsite had no detectable levels of any of these compounds (Table3).

A potential exception to the distance/mobility generalizations proposed above is found in the brain coral collected from the hull of the USN*Killen*(Table3). This coral contained 252 mg/kg of TNT, which based on the predicted decline (Fig.9), suggests that unexploded ordnance should be close by. However, at the time of collection, no ordnance was observed. The two alternative explanations for high TNT concentrations in this coral are: (1) toxic chemicals are dispersing considerably greater distances than the exponential decay hypothesis articulated above would suggest, or (2) unexploded ordnance litters the*Killen*wreck site, and even if it could not be seen with the naked eye, live munitions were very close at hand. We favor the latter hypothesis and interpret the presence of TNT in the brain coral from the USN*Killen*hull as the expression of leaking ordnance in the immediate vicinity of the collection site.

Taken collectively, these data suggest that UWUXO pollution on Vieques is "point source." If you pick up the bombs, you will get rid of the problem.

Conservation Imperatives on Vieques

Unique Status of the Coral Reefs of Vieques

Coral reefs are in decline globally [63] and especially in the Caribbean [31]. Reefs harbor extraordinary biological diversity, at both the species level, but especially at the phyletic and higher taxonomic levels [68]. Standard EPA 40

m^2belt transects conducted in the Florida Keys National Marine Sanctuary (Rock Key and Carysfort Reef) contain a maximum of 19 scleractinian species [70]. By contrast, Ensenada Honda contained 22 and 23 coral species, respectively (Table4), attesting to the high biodiversity of this locality. The coral reefs of Puerto Rico and Vieques were also among the first Caribbean reefs studied [83]. With coral reefs in decline worldwide, the preservation and restoration of the coral reefs on Vieques is of international importance [55].

Ecosystem Integrity

We are almost wholly ignorant of the effects that high explosives and heavy metals have on ecosystem health and ecosystem function. We do not know which of these materials are toxic to marine organisms; we do not know which ones bioaccumulate; we do not know which are degraded by seawater or by marine microbial communities; we do not know which nitrosamine degradation products are toxic; and we do not know how long these compounds persist in the marine environment. In their literature review of*Munitions Dumped at Sea*, Beddington and Kinloch [16] state, “We have been unable to find appropriate quality assured data to address Persistence, Bioaccumulation and Toxicological (PBT) criteria,” which are and must be “the basis for assessing hazardous substances.” Until humankind accepts the relationship between human health and environmental health, we are unlikely to get answers to most of these important questions.

Toxicity of High Explosives

Of all the compounds listed in Table3, we know most about the adverse effect of TNT on marine life. Conventional high explosives, including TNT and other nitro-amine compounds can be extremely toxic to marine organisms: “The chronic toxicity of sediment-associated 2,4,6-trinitrotoluene (TNT) to the marine polychaete*Neanthes arenaceodentata*and the estuarine amphipod*Leptocheirus plumulosus*was evaluated. Survival was significantly reduced at a tissue concentration of 61 mu g TNT/g wet wt tissue in*N. arenaceodentata*and at 6.3 mu g TNT/g wet wt tissue in*L. plumulosus*and reproduction was significantly reduced at a tissue concentration of 6.3 mu g TNT/g wet wt tissue in*L. plumulosus”*[37]. The authors interpret these data as demonstrating that: “both*N. arenaceodentata*and*L. plumulosus*are sensitive to the presence of sediment-associated TNT and that more information is needed about the toxicity of TNT to benthic fauna to facilitate risk assessment and management of TNT-contaminated sites” [37]. Given the high concentrations of TNT measured in some of our sediment samples (Table3; Figs.9and10), the Green et al. [37] study is particularly apropos to our study sites near Roca Alcatraz.

Several other nitrosamines have also been shown to be toxic to marine invertebrates. Lotufo et al. [49] tested “the toxicity of nitroaromatic (2,4-diaminonitrotoluene [2,4-DANT] and 1,3,5-trinitrobenzene [TNB]) and C-14-labeled cyclonitramine compounds hexahydro-1,3,5-trinitro-1,3,5-triazine [RDX] and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine [HMX]) following 10- or 28-d exposures to spiked sediments on the marine polychaete*Neanthes arenaceodentata*and the estuarine amphipod*Leptocheirus plumulosus*. Survival was significantly reduced by nitroaromatics at nominal sediment concentrations as low as 200 mug/g, with*L. plumulosus*being more sensitive than*N. arenaceodentata*. Growth was significantly decreased at sublethal concentrations of 2,4-DANT for*N. arenaceodentata*. Reproduction, measured only with*L. plumulosus*, was significantly decreased only in the highest RDX treatment and also in the lower TNB treatment.” These are the compounds we found*in situ*on the reef (Table3). Both polychaetes and amphipods are common in tropical marine waters.

Nipper et al. [59] developed “a toxicity database for ordnance compounds using eight compounds of concern and marine toxicity tests with five species from different marine phyla. Toxicity tests and endpoints included fertilization success and embryological development with the sea urchin*Arbacia punctulata*; zoospore germination, germling length, and cell number with the green macroalga*Ulva fasciata*; survival and reproductive success of the polychaete*Dinophilus gyrociliatus*; larvae hatching and survival with the redfish*Sciaenops ocellatus*; and survival of juveniles of the opossum shrimp*Americamysis bahia*(formerly*Mysidopsis bahia*).” The studied ordnance included 2,4- and 2,6- dinitrotoluene, 2,4,6-trinitrotoluene, 1,3-dinitrobenzene, 1,3,5-trinitrobenzene, 2,4,6-trinitrophenyl-methylnitramine (tetryl), 2,4,6-trinitrophenol (picric acid), and hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX). This list is almost identical to the nitrosamines we found on Vieques (Table3). Their data demonstrate that, “the most sensitive toxicity test endpoints overall were the macroalga zoospore germination and the polychaete reproduction tests. The most toxic ordnance compounds overall were tetryl and 1,3,5-trinitrobenzene. Picric acid and RDX were the least toxic chemicals tested overall” [59]. Their study identified what may turn out to be an important -generalization: “Among the dinitro- and trinitrotoluenes, toxicity increases with the level of nitrogenation” [59]. If substantiated, this research and development targeting the removal or degradation of these particular compounds may produce the most efficacious result.

Laboratory studies on the effects of TNT on fish have only been conducted on freshwater species. While investigating the freshwater catfish,*Ictalurus punctatus*, Ownby et al. [62] demonstrated that, "bioconcentration of TNT was low due to rapid biotransformation and elimination of TNT. Muscle and skin had lower concentrations of TNT than the whole fish, indicating that ingestion of fish filets would result in decreased exposure to human consumers." Working on the rainbow trout,*Oncorhynchus mykis*, Ek et al. [29] found a "dose-dependent increase in TNT, 2-amino-4,6-dinitrotoluene (2-ADNT) and 4-amino-2,6-dinitrotoluene (4-ADNT) in the hydrolyzed bile of TNT-treated fish. These results indicate that the fish are able to detoxify and excrete TNT, and suggest that the detection of TNT, 2-ADNT and 4- ADNT in bile may be suitable as a direct marker of exposure to TNT." They also state that, "Harmful effects of TNT on aquatic organisms have been reported well below its water solubility of 130 mg/l at 20°C [1]. Fish have been shown to be relatively sensitive to TNT with LC50-values ranging from 0.8 to 3.7 mg/l [76], and decreased survival of rainbow trout fry after 60 days has been observed at 0.24 mg/l [10]. To our knowledge, no data are available regarding the biochemical effects of systemic TNT-exposure in fish." An important finding of their study [28] is that "chemical analysis of 2,4,6-trinitrotoluene in blood plasma from fish may be suitable as a direct confirmation of exposure to this compound. Increased methaemoglobin levels may be a promising aid as a general biomarker in field monitoring of possible exposure in fish caught close to ammunition dump sites." If this finding holds for tropical marine fish as well as rainbow trout, then it may provide a direct way to detect exposure of the fishing stock to explosive compounds in Vieques coastal waters.

Citing the toxicity of TNT in freshwater, Ek et al. [28] comment that, "2,4,6-trinitrotoluene is the major explosive in ammunition dumped in Swedish waters, and bioassays with Microtox (*Vibrio fischeri*), green alga (*Pseudokirchneriella subcapitata*, =*Selenastrum capricornutum*),*Daphnia magna*and*Nitocra spinipes*have confirmed it to be the most toxic of the commonly used nitroaromatic explosives. The compound is mutagenic and toxic to plants and animals and is relatively persistent in the environment. Laboratory studies have shown that the median lethal concentrations after 24 or 48 h for invertebrates ranged from >4.4 to 29 mg/l" [85].

Stucki [75] notes that "The toxicity of aromatic nitro compounds is of great importance because of their wide distribution in munitions: 2,4,6-trinitrotoluene (TNT) is present in bombs and shells, and dinitrotoluene (DNT) is used as an energetic additive in propellants. DNTs normally are more toxic for mammals than TNT, but TNT is a stronger toxin for fishes. Data for TNT and DNTs show the following LC50 (Lethal Concentration, 50% kill): 2,4,6-TNT (2.4 mg/l); 2,4-DNT (35.5 mg/l); and 2,6-DNT (19.8 mg/l)."

Also working with freshwater fish, Bailey et al. [10] showed that "in a two-generation study, a TNT concentration as low as 0.04 mg/1 decreased several reproductive parameters of fathead minnows."

From our own data, the star coral (*Montastraea annularis*) in physical proximity to the bomb exhibited signs of stress including discoloration, presumably due to a loss of symbiotic algae and reduced chlorophyll content (Fig.4[lower right]). This colony had TNT concentrations of 600 mg/kg as well as high concentrations of 1,3,5-Trinitrobenzene, 1,3-Dinitrobenzene, and 2,4-Dinitrotoluene +2,6-Dinitrotoluene (Table3; Fig.9), which may have caused or contributed to its poor health.

In an experimental study on the Indo-Pacific coral reef damselfish,*Dascyllus aruanus*(L), Jameson [43] examined the toxic effects of chemicals leaching from explosive depth charges from a sunken war ship. Using varying concentration of materials leaching from UWUXO, Jameson found that "exposure to 'yellow powder' (6% water, 83% ammonium picrate, 10% aluminum powder, and 1% benzene-soluble organics) resulted in a 48-hour LD_{50}value of 188 mg/l and a 96-hour LD_{50}value of 95 mg/l. Experiments using 'black powder' (34% water, 4% ammonium picrate, and 42% inert humic acid-type polymer) resulted in a 48-hour LD_{50}value of 1,200 mg/l and a 96-hour LD_{50}value of 1,000 mg/l." These data show that the longer the exposure time, the lower the leachate concentration required to kill this coral reef fish. Different explosive compounds have different lethal doses.

Multiple Stressors/Multiple Effects

To say we know little of the effects of these toxicants alone is to fully admit that we know absolutely nothing about their effects in combination. In an experimental study on the effects of elevated salinity and temperature, Porter et al. [69] demonstrated synergistic effects with these two stressors. The combination of elevated salinity and elevated temperature lowered coral photosynthesis and survival faster than either of the stressors alone. Multiple stressors are worse than single stressors. Vieques is a multiply stressed reef.

Ecosystem Pathways/Flow Patterns

To describe how a healthy ecosystem functions, traditional ecosystem models define four components of material and energy flow within the community: (1) the kind of materials moving through, or recycling within, an ecosystem, (2) the rate at which these materials flow through the system, and (3) the direction of these material flows. In addition, ecosystem models attempt to quantify (4) patterns of energy flow through the system. Our knowledge of these processes is rudimentary, at best, for coral reefs in general [54]. For coral reefs in the Vieques LIA, neither their chemistry nor their physics is traditional. The practice and conduct of war is characterized by stockpiling, disposal, and detonation of explosive compounds and is "largely distinguished by immense and concentrated energy flows, severe disturbances, habitat destruction, chemical contamination, landscape cratering, vegetation removal and destruction" [50]. Rather than presenting anything close to an ecosystems model, Figs.9and10instead attempt to define some of the unique features on Vieques that will influence how an ecosystem model for this coral reef would be constructed.

All of the compounds depicted in Table3and Fig.10are manufactured by humans and do not exist in the natural world. All are multiply hazardous, either as explosives or as carcinogens. How and where these compounds move on the reef is profoundly important, and not just in the context of whether they might damage the commercially valuable foodstuffs that can be extracted from it. We also need to know in what ways these compounds may have compromised this biologically diverse tropical marine ecosystem. Despite the fact that there are no data on the ecosystem effects of the substances listed in Table3, there is really no reason to believe that these chemicals are not having an adverse effect. The rush to certify a clean bill of health for human consumption of a narrow range of commercially exploited fish and shellfish does not, in any way, prove that the ecosystem that supports these commercially valuable stocks is not in jeopardy. Further, the absence of toxic materials in foodstuffs from the reef does not guarantee that these materials will not find their way into the human food chain at a later date.

In many ways, the ecosystem concept [35] was born in studies examining the aftermath of war, first in Odum and Odum's pioneering studies [60] on the Marshall Islands, where the US tested atomic bombs, and later at the Savannah River Ecology Laboratory in South Carolina, where the US built them. Ironically, many of the concerns over the safety of Vieques coral reefs also arise from those seminal events in the history of US warfare, since the USN*Killen*had also come from atomic tests in places very close to the location of Odum and Odum's important study. In the same sense that unique and easily identifiable physical signatures of fission products associated with nuclear bomb blasts and nuclear fallout have been useful in coral growth and coral reef ecosystem studies [21], it is possible that the equally distinctive chemical signatures of high explosives (Table3) may also contribute to a better understanding of material flow on a coral reef.

Heavy metals, which are somewhat easier to measure at low concentrations in saltwater than explosive compounds, are giving us important insights about material movement through the Viequean coral reef. Herrera et al. [40] found high concentrations of aluminum, arsenic, iron, nickel, zinc, cadmium, cobalt, and lead in sea grasses (both*Thalassia testudium*and*Syringodium filiforme*) around Vieques. These authors noted a close relation between military activities and heavy metal pollution in Viequean submarine plants.

Massol-Deya et. al. [53] confirmed these findings for lead concentrations in*Syringodium filiforme*. Their study is particularly relevant to an investigation of coral reef ecosystem dynamics. The sea grass,*Syringodium*is commonly found in shallow waters in southern Puerto Rico and is preferentially fed on by coral reef fish rather than other marine plants such as*Thalassia*[79]. Massol-Deya et al. [53] noted that, "levels of lead detected in*Syringodium filiforme*from the AFWTF indicate the dispersion of metals throughout the marine food chain. The content of lead in*S. filiforme*cannot be explained solely as a result of natural processes. Further, heavy metals were undetectable in seawater when military practices did not take place. In May 2003, military operations ceased at the AFWTF, and samples obtained in 2004 of*S. filiforme*showed lower concentrations ($p < 0.05$) of cobalt, copper, nickel and lead to those levels observed in 2001. At the AFWTF however, the level of these elements are still higher ($p < 0.05$) than mainland, Puerto Rico. The level of lead and other elements in*S. filiforme*demonstrate the potential for dispersion and dangerous bioaccumulation along the marine food chain. Fishes, crustaceans, and manatees directly or indirectly consume this marine plant. The US Fish and Wildlife Service reported manatees feeding in Vieques and most intensively near the former AFWTF. Our results from the samples taken at the AFWTF indicate mobilization of undesirable trace elements through the marine and terrestrial food web. Since plants naturally remove heavy metals from soils, they could be employed for the restoration of this and similarly contaminated sites. Understanding the dynamics of trace elements and other pollutants at this location could help establish management practices intended to prevent further exposure to human and endangered species. In turn, mitigation and better restoration mechanisms might be developed."

Several studies ATSDR [7,9] have also found high lead concentrations in both marine fiddler crabs and terrestrial land crabs. Data from both the US Fish and Wildlife Service's 2001 study and ATSDR's 2003 shellfish assessment are in agreement that land crabs and fiddler crabs from Vieques contain heavy metals and pesticides, but, from a human toxicological perspective, they conclude that "since the FWS samples were analyzed as whole body, the data from the report are useful to evaluate ecological contamination, but cannot easily be converted for evaluating human health" [9]; and finally that, "metals were detected in land crabs. However, the levels were too low to be of health concern for people eating them" [7].

Bioaccumulation Patterns

The potential for high explosives (or their degradation products) to bioaccumulate in tropical marine environments is unclear. This important lacuna is certainly more of a reflection on our lack of knowledge of how a coral reef ecosystem works than of a substantive debate between well-researched alternatives. Beddington and Kinloch [16] state, "Conventional material including TNT and variants can be extremely toxic to marine organisms. There does also appear to be the potential that this material could concentrate in food chains after some degree of absorption has occurred. As far as we are aware, the toxicity of products of TNT in sea water has not been addressed in any detailed way in the current literature." Ek et al. [28], citing their own study and that of ATSDR, however, believe that this is not an issue for TNT, suggesting that, "with a log octanol/water partition coefficient (Kow) of 1.6–2.7, this suggests that TNT will not bioconcentrate strongly in plants and animals or biomagnify in food chains" [1].

Even if bioaccumulation of TNT is not occurring, it appears that the extraordinarily high concentration gradients emanating from unexploded munitions on the reef (Table3; Fig.9) are sufficient to send this toxic substance out into the coral reef ecosystem and its living biota (Fig.10).

As opposed to high explosives, there seems to be unequivocal evidence for the bioaccumulation of heavy metals in the Vieques coral reef ecosystem. Massol-Deya et al. [53] comment, "levels of lead detected in*Syringodium filiforme*from the AFWTF demonstrate the potential for dispersion and dangerous bioaccumulation along the marine food chain." This also appears to be the case for cadmium [52] (report cited in [9]). This publication compared to the levels of heavy metals detected in fiddler crabs in Icacos Lagoon (Fig.2) to levels found in the soils. They reported cadmium concentrations in fiddler crabs10–20 times higher than in the soils and concluded that biomagnifications of cadmium was occurring.

Fate and Transport Processes in Fresh- and Saltwater Environments

TNT is quite persistent in aquatic environments. Hoffsommer and Rosen [42] showed that "2,4,6-trinitrotoluene was stable in seawater for 108 d at room temperature, demonstrating its resistance to hydrolysis." Brannon et al. [19], compared the environmental fate and transport process of explosives in saline and freshwater systems. From laboratory tests, they found that dissolution rates, transformation rates, and absorption rates of TNT, RDX, and HMX were generally in close agreement regardless of whether the observations were performed in fresh or saltwater. They concluded, "the (existing) freshwater database for explosives fate and transport process is adequate for prediction of explosive fate and transport in marine environments." If this generalization holds true under the hydrologically dynamic environment of a coral reef, then the use of studies published from freshwater environments, such as lakes in Switzerland [75] and Sweden [28] may save considerable time in trying to populate a coral reef ecosystem model heavily dependent on the dissolution, adsorption, and transformation rates of these exotic chemicals.

Potential for Site Cleanup

Underwater Range Maintenance

Range maintenance, the removal of UXO from target ranges, is standard operating procedure on all terrestrial bombing and small-arms target ranges all over the world. However, there is no such protocol for seafloor environments. This practice appears to stem from an official policy of ordnance abandonment. Out-of-sight, out-of-mind thinking prevails, but as most ecologists know, it rarely, if ever, works. Citing gross contamination of the coastal environment "for 100 years by the US Navy," the US Environmental Protection Agency formally proposed the Atlantic Fleet Weapons Training Area in August, 2004, and placed it on its National Priorities List (NPL) of Superfund Sites in February, 2005. At this time, Vieques, and significantly also the waters surrounding Vieques and Culebra, were included in the NPL designation. Because of its assignment to NPL, most observers expected that cleanup of both terrestrial and marine environments would start immediately [15].

This did not happen. Although the Department of Defense had been held accountable under the US Environmental Protection Agency laws pertaining to CERCLA/Superfund Sites since 1985, in 2002, the Pentagon successfully sought exemption from almost all environmental laws and regulations, citing preparedness needs in a time of heightened national security concerns [12].

Our data demonstrate unequivocally that pollution on Viequean coral reefs is classically point source (Fig.9). The removal of munitions from the reef also removes the explosive compounds they produce. We expect that ordnance removal will have an immediate and beneficial effect on the reef and its inhabitants. Picking up the bomb removes the problem. The challenge is to find a way to remove ordnance without destroying the reef in the process.

The Underwater Ordnance Removal Apparatus

Open-air detonation and abandonment are used today as viable options at some locations, but for various reasons, neither option is desirable or acceptable. Clearly there is a need to conduct remote operated non-destructive remediation of hazardous defense wastes from a marine environment in a safe, reliable, and economical manner.

Our solution is the Ordnance Harvester (Fig.11). It harnesses the power of hydraulics to operate a mechanical arm which manipulates various attachments for the recovery of intact or case-corrupted munitions, bulk containers or their content, general material transfer, and de-arming (Fig.11[top]). A prototype was designed, built, and successfully tested during sea trials in Key West Florida in 2005 (Fig.11[lower left and lower right]). In 2008 the technology was awarded a US patent.

Open image in new window
Fig. 11

The Underwater Ordnance Removal apparatus (*top*) is capable of picking up and removing 2,000 lb bombs from the sea floor (*lower left*). It is a remote-controlled underwater hydraulic apparatus with a grab (*lower right*) that is capable of lifting and placing UXO in a pontoon basket, which can float ordnance to the surface for disposal

Electric power and control signals are sent through a tether to allow the operator to remain a safe distance from the work site. Operator control is enhanced through the use of closed circuit TV, sub bottom profiling sonar, and ferrous metal detection. The power of hydraulics and precise controls permit the safe handling of sensitive, yet heavy hazardous materials. No divers are required for recovery operations, thereby reducing the potential for diver related casualties through exposure to harmful agents or other hazards. Under the best circumstances (shallow, clear water, relatively flat rock or sandy bottom, heavy concentrations of targets), up to 30 intact 105 MM projectiles can be harvested per hour. Beyond that, the variables and specific demands of any given site can greatly reduce the rate of munitions retrieval.

There is no limit on how deep the system can be deployed, but depths less than 15 m permit the use of an above surface mast mounted geo-positioning antenna; beyond 15 m a more complex subsurface unit is required. Depths greater than 100 m require higher rated connectors, seals, and an advanced launch and recovery system. The Ordnance Harvester can be launched in several ways; it can be driven directly into the water from shore, lowered to the worksite with a crane, or as required in deep water applications, launched and recovered using a dedicated system specific launch and recovery platform. The base model Ordnance Harvester has a knuckle boom with a three-meter reach and 360° swing. In this configuration the grapple on the end of the boom can grasp and handle objects larger than 1 m in diameter weighing over one metric ton and buried up to one half meter below the sea bed. The system is mounted on four adjustable legs used to maintain an upright attitude on irregular terrain. In this configuration, the system must be lowered into position to within 3 m of the target. A rubber tracked mobility chassis option is available for more independent operations. When coupled with available geo-referencing technology and magnetic detection, it can clear a pre-determined lane through scattered contamination or clear a designated area using the grid clearance method.

The ability of the mechanical arm to safely handle sensitive munitions also provides the capability for*in situ*de-arming of fused munitions through the incorporation of abrasive water jet cutting techniques. This process greatly reduces the dangers and costs associated with transporting "armed" munitions. The mechanical arm also offers precise placement of various kinds of dredges to collect scattered small arms ammunition, crumbled solids, or pools of heavy liquids.

Since no divers are used, the only time the system needs to stop harvesting is for maintenance (about 8 h maintenance for every 50 h worked). Decontamination costs are therefore reduced as are the chances of a diver casualty through chemical exposure. Operations can continue at all hours to save on logistics and to reduce disruptions of normal activities near the site. The spread of contamination is limited to the area where the target is acquired, since immediately afterwards it is placed in an appropriate vessel for transport to a disposal facility. If deemed necessary, industrial grade heat-shrink plastic can be applied to the target prior to placement in a transport vessel. Where a diver struggles to attach a lifting harness to smooth skinned targets like bombs or larger projectiles, the mechanical arm and grapple of the Ordnance Harvester obtains a positive grasp in a single motion and then carefully maneuvers the target into the appropriate transfer vessel which limits contamination of the water column. Where corroded metal drums, the remains of their contents, or munitions with a weakened case are involved, a diver has limited options, but the Ordnance Harvester can quickly replace its grapple with a clamshell attachment to fully encase the target before the lift is made and then transfer the material to the appropriate container.

Site Restoration

Challenges Associated with Limestone-Entombed Ordnance

Magnetometer surveys reveal that a substantial amount of metallic shrapnel and UWUXO is entombed within the reef (Figs.4[upper right], 5, and 7). Magnetometers have the unique ability to accurately determine the presence of metallic objects buried from view [13]. This property has made them invaluable in surveying hazardous waste sites [33] and for locating UXO on abandoned military bases [64,65]. The ability of a magnetometer to detect a metallic object is dependent on three factors: (1) the elemental composition of the metal (e.g. iron is most easily detected; aluminum least easily), (2) the mass of the object (heavy objects are detected more easily than light weight objects), and (3) the distance to the object (closer objects are detected more easily than distant objects) [58].

Figure7shows that metallic shrapnel was detected in almost every quadrant of the crater's wall. Further, this diagram also demonstrates that a majority of the metal embedded in the crater wall is in the south and west-northwest quadrants. We speculate that as bombs or shells came in from firing positions to the south, that the crater wall is blown away in the northern sector and that shrapnel that stays on site is deflected backwards and to the left where it lodges in the crater walls. Although we would recommend that a full magnetometer survey of the entire reef should be conducted within the LIA, initially we also recommend that what lies within the bedrock be left there.

Marine Sanctuary Status

Without doubt, cleanup and restoration of the Vieques coral reef will be complex. "In addition to heavy metals and ordnance, remediators will have to contend with the degree of dispersion, impacts on lagoons, mangroves, and coral reefs, and the dispersion and solubility of toxics in a tropical rather than temperate climate" [15]. In addition, "such locations potentially carry cumulative burdens of warfare impacts, including mixed-age pollutants, repeated soil compaction and sterilization, and various generations of UXO's" [50]. This does not mean that we should not try.

Following World War II, the Geneva Convention created an internationally binding treaty meant to limit the barbarity of war. The Geneva Convention Codicil on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) states that, "Methods of warfare likely to cause environmental damage, and thereby jeopardize the health and survival of the population are strictly forbidden." ENMOD has been ratified by 70 countries (the US is not one of them), yet it remains largely unknown and unenforced [50]. Documentation of substantial and long-term toxicological effects on the coral reef ecosystem contributes to the argument that the unremediated use of Isla de Vieques for war preparation violates both the letter and spirit of the Environmental Modification codicil (EnMod) of the Geneva Convention.

An attempt to clean up Vieques and address both environmental and human health issues on the island would go a long way toward bringing the US into conformity with the central tenet of international law. The Helsinki Commission (HELCOM), working with the World Health Organization, has proposed that the restoration of lands impacted by war be of the highest priority for global environmental cleanup efforts. At the very least, the consensus from the HELCOM working group was that, "some kind of environmental monitoring of the dumpsites ought to take place, and that research in the behavior of persistent chemical warfare agents in the marine environment must be carried out too" [84].

We recommend that the Vieques coral reef be accorded international environmental protection. Further, we recommend that site cleanup begin immediately. It is critical that all marine habitats, perhaps down to the 100 depth contour (the functional limit for coral reef development), be included in the conservation plan. The US National Park Service, with its traditional strengths in managing both terrestrial and aquatic environments, might be the best agency to implement this conservation plan.

In a 1982 survey by the Puerto Rican Department of Natural and Environmental Resources and the US Navy, the inspection team concluded that the wreckage of the USN*Killen*is "an important marine habitat and that no action should be taken to remove the remaining hulk because it would be ecologically damaging to attempt to do so" [23]. The site does indeed function as an "artificial reef" [24] and is visited frequently by fishing boats from both Esperanza and Isabel Segunda (Fig.1). We concur that, once live ordnance is removed from this site, the site should be left undisturbed, and perhaps be accorded Special Protected Area status in keeping with the historical significance of the USN*Killen*both to the people of the United States, and especially now, to the people of Puerto Rico.

Cleanup of the navy bombing range on Kaho'olawe in Hawaii [46] offers perhaps the most precise parallel with the challenges faced in Vieques. Kaho'olawe was turned over to the state of Hawaii in April 2004 after a 10-year, $460 million cleanup. While the original remediation goal was to remove 100% of surface ordnance and 30% of subsurface munitions, the military accomplished 77% and 9% respectively. Most of that Hawaiian island still remains off-limits [15]. Hawaii is represented in the US Congress by a full complement of members of both the House and the Senate. Puerto Rico is represented by a single Resident Commissioner in the House of Representatives, but not by either a fully voting Congressperson or Senator. At present, we have only, "imprecise estimates on the cost and duration of the Vieques cleanup. In March 2004, Navy Undersecretary, Hanford Johnson, said cleanup of toxics from 89 acres in the east and 500 acres in the west would cost $114 million and would take 15 years. Christopher Penny, Navy Remedial Projects Manager for the western side, said that cleanup would take at least a decade" [56]. "As of December 2004, only $4.3 million had been spent on the west side of Vieques for cleanup [27]" (Baver 2006 [15]).

Under CERCLA/Superfund legislation, a Restoration Board has been established on Vieques with citizen input to advise the site cleanup process, but as this paper goes to press, it is unclear if the political power required to initiate and pay for an ecosystem restoration on this scale will be forthcoming.

The Vieques Paradox [86] remains: despite the fact that it is one of the most beautiful places on earth, within its borders are also some of the most toxic places on earth.

Conclusions

Ecological surveys

- Coral reefs in the Live Impact Area on the eastern end of Bahia Salina del Sur have been severely disrupted by military activity.
- Military debris can be found on top and within the coral reef, including:
    - Unexploded bombs, artillery shells, and shell casings on the coral reef and in the adjacent sea grass bed,
    - UXO and military debris lying on top of coral reef organisms,
    - Detonation craters blown into the bedrock and framework of the reef,
    - Parachutes from illumination flares draped over coral reef organisms, and
    - Unexploded bombs leaking toxic materials into the coral reef.
- There is a statistically significant inverse correlation between the density of military ordnance and several measures of coral reef health, including the number of coral species, the number of coral colonies, and coral species diversity.
- Reefs with the highest concentrations of bombs and bomb fragments have the lowest health indices and the lowest coral species diversity.
- Magnetometer readings on the eastern end of Vieques reveal the presence of metallic shrapnel embedded in the reef.
- Magnetometer readings from holes and depressions on the reef are consistent with a detonation origin for the craters and are inconsistent with a hurricane origin for these craters.

Radiological surveys

- There are no radionuclides associated with nuclear fallout or atomic bomb testing found in any of the marine waters, sediments, coral, or fish from Vieques.
- The isotopic distribution of gamma activities for ^{238}U, ^{232}Th, ^{40}K, and ^{226}Ra in the samples are of natural origin, as represented by their corresponding ratios.
- Neither metal samples nor biota collected from the USN *Killen* site show any radionuclides that would have been associated with its participation in nuclear testing on the Marshall Islands in 1958.

Chemical surveys (Bahia Salina del Sur)

- Seawater samples collected from the USN *Killen* site contained no detectable explosive residues.
- RCRA heavy metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) in water were all below EPA Risk-Based Concentrations and EPA Drinking Water Maximum Contaminant Level Standards.
- Most sediment samples collected from the vicinity of the USN *Killen* contained no detectable explosives residues.
- All RCRA elements in sediments were below levels in the Hatillo (P.R.) samples that served as background.
- 1 of 6 coral samples collected in the vicinity of the USN *Killen* contained detectable levels of explosive residues. The proximity of this individual, with 252 mg/kg TNT, to unexploded munitions is unknown.
- Metal residues in coral samples from Bahia Salina del Sur were lower than levels found in control corals from Hatillo, P.R.
- Fish composite samples (Bahia Salina del Sur, Sites 1 and 2) and the lobster composite samples (Site 1) contained only trace levels of explosive residues.
- Barium, cadmium, chromium, mercury, selenium and silver residues were below EPA Risk-Based Concentration Guidelines for fish composite samples from Bahia Salina del Sur Sites 1 and 2.
- The lobster composite from Bahia Salina del Sur contained arsenic at 38.4 mg/kg, which is well above the EPA Risk-Based Concentration Guideline of 0.16 mg/kg, and may warrant a consumption advisory.

Chemical surveys (Roca Alcatraz)

- Everything in and around a corroding, submerged 2000-pound bomb at Roca Alcatraz was contaminated (and in some instances highly contaminated) by explosive residues.
- Water and the flesh of many living organisms at this reef site contained seven known carcinogens:
    - 1,3,5-Trinitrobenzene
    - 1,3-Dinitrobenzene

    - 2,4,6-Trinitrotoluene
    - 2,4-Dinitrotoluene + 2,6-Dinitrotoluene
    - 4-Nitrotoluene
    - 2-Nitrotoluene
    - Hexahydro-1,3,5-Trinitro-1,3,5-Triazine (4,120 ppb).
- Seawater at the bomb's surface exceeded safety standards for every compound detected, including 1,3,5-Trinitrobenzene (11,525 ppb); 1,3-Dinitrobenzene (18,500 ppb); 2,4,6-Trinitrotoluene (85,700 ppb); 2,4-Dinitrotoluene + 2,6-Dinitrotoluene (82,500 ppb); 2-Nitrotoluene (40,500 ppb); and Hexahydro-1,3,5-Trinitro-1,2,5-Triazine (4,120 ppb).
- Sediment samples at this site also contained high concentrations of TNT as well as carcinogens (1–5) and (7) from the above list.
- Every animal tested near UWUXO contained at least one potentially toxic compound. For instance:
    - Coral [600 mg/kg TNT; 1,3,5-Trinitrobenzene (250 mg/kg); 1,3-Dinitro (250 mg/kg); and 2,4-Dinitrotoluene +2,6-Dinitrotoluene (250 mg/kg)]
    - Feather duster worm [40,200 mg/kg TNT; 1,3,5-Trinitrobenzene (23.9 mg/kg); 1,3-Dinitrobenzene (9.52 mg/kg); and 4-Nitrotoluene (95.5 mg/kg)]
    - Sea urchin (721 mg/kg TNT)
    - Damselfish [did not contain detectable levels of TNT or RDX by immunoassay (<0.5 mg/kg) or HPLC (<1.2 mg/kg, <1.3 mg/kg, respectively), but did contain trace levels (4.6 mg/kg) of 1,3,5-Trinitrobenzene]
- The toxic chemicals found in these reef organisms do not occur in nature, but instead come exclusively from man-made explosive ordnance.
- Concentrations of these substances in fish from this site approach, but do not exceed, EPA's Risk Based Concentrations for commercially edible seafood.
- Concentrations of these substances in several of the non-commercial species tested (e.g. the feather duster worm, coral, and the sea urchin) greatly exceed EPA's Risk-Based Concentrations for seafood.
- Coral samples collected at the site had a lead concentration of 195 mg/kg.
- The presence of explosive residues in organisms from this site demonstrates conclusively the movement of these hazardous compounds into the marine food chain.

Patterns of hazardous material contamination

- An organism's proximity to unexploded ordnance and its mobility seem to determine the concentration of toxic chemicals in its body:
    - the closer an organism is to a leaking bomb, the higher its body burden will be, and
    - the less mobile (and therefore more sessile) an organism is, the higher the concentration of toxic substances will be.
- An exception to this generalization may have been found in coral collected from the hull of the USN*Killen*, far removed from visible ordnance, but which nevertheless had high concentrations of TNT.
- For both explosive compounds and heavy metals, the concentration of toxic substances dissipates rapidly as the distance from the bomb increases to non-detectable levels at 2 m from the bomb.
- Explosive compounds and heavy metals decline exponentially.
- Based on these patterns of decline, contamination on the Vieques coral reef is considered to be classical "point-source" pollution.
- Removing the UWUXO will remove the problem.

Recommendations

Limited health advisory for the site

- Because carcinogens leaching from corroding UWUXO have entered the marine food chain, we recommend that the Commonwealth of Puerto Rico place the USN*Killen*site on a Limited Health Advisory watch list banning both commercial and recreational fishing from the wreck site and the offshore area immediately in front of Rocas Alcatraz.
- We recommend that this Health Advisory remain in force until such time as lowered arsenic levels can be assured for fish and lobster coming from the affected area.

- Based on the presence of heavy metal and chemical contamination in some of the seafood collected from the USN*Killen*wreck site, we recommend that this site be designated as a fisheries no take zone.

Superfund Site cleanup

- Since UXO on the Vieques coral reef is both an environmental and a health hazard, we recommend that the EPA implement its Vieques Superfund Site cleanup.
- As part of this cleanup, we recommend a detailed survey be conducted to determine the total number and type of UWUXO in the waters surrounding the LIA.
- Since the distribution of explosive compound and heavy metal pollution is point source, we recommend that UWUXO be picked up first and disposed of in as environmentally friendly way as possible.
- Non-destructive removal of UWUXO is recommended and should be employed on exposed munitions only.
- UWUXO buried beneath the reef, or located beneath the sea floor, should be left in place.

Creation of a marine protected area

- The eastern end of Isla de Vieques should be designated as a Marine Protected Area, under the aegis of either the US National Park Service (Department of Interior) or the Marine Sanctuary Program (Department of Commerce).
- Based upon the cultural heritage value of the USN*Killen*site, we recommend that this area be designated as an underwater archaeological preserve and protected as a "no take zone" with respect to the cultural artifacts submerged there.
- Given the fragile nature of coral reef resources in this area, we recommend the installation of permanent mooring buoys to allow visitors to approach the site safely, causing as little damage as possible.
- We recommend that as part of the site cleanup and reef restoration, a long-term ecological research and monitoring program be initiated on the coral reefs of Vieques.
- We also recommend a carefully designed research program to define the origin, pathways, and transport mechanisms of heavy metals and explosive compounds found in biota at the site.

Peace and security implications of environmental modifications on Vieques

- Our research documents hotspots of marine environmental pollution on Vieques, and demonstrates that toxic substances leaching from conventional weapons on the seafloor have entered the Vieques coral reef ecosystem.
- Our research raises serious concerns about the potential movement of these hazardous materials within and beyond the Vieques marine environment.
- Documentation of substantial and long-term toxicological effects on the coral reef ecosystem contributes to the argument that the unremediated use of Isla de Vieques for war preparation violates both the letter and spirit of the Environmental Modification codicil of the Geneva Convention.
- On Vieques, commonly accepted definitions of homeland security and national defense are called into question by well-documented and long-standing public health and environmental issues.

Footnotes

1. 1.

   www.epa.gov/safewater/consumer/mcl.pdf (2004) and/or RBC Guidelines available at web site: www.epa.gov/reg3hwmd/risk/index.htm (2004).

2. 2.

   Risk level = 1/100,000 in www.epa.gov/ost/fishadvice/volume1/v1ch5.pdf (2004).

3. 3.

www.epa.gov/reg3hwmd/risk/index.htm (2004).

Notes

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