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Condition of *in situ* unexploded ordnance

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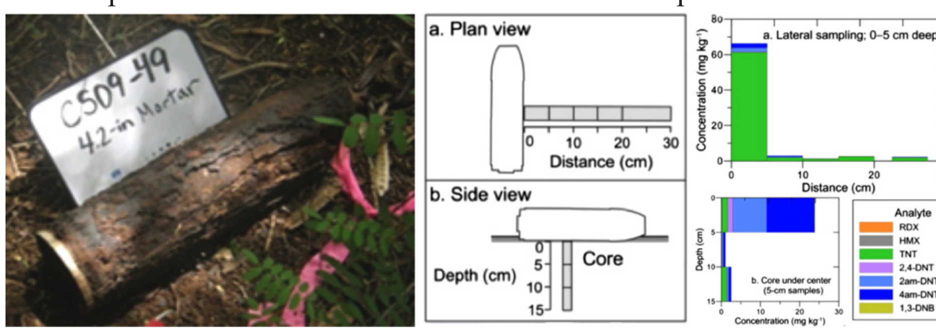
HIGHLIGHTS

- We sampled soils beneath 42 UXO, and found eight leaking explosives.
- Oxidation swells some UXO casings, leading to their catastrophic failure.
- Explosive concentrations and ratios indicate how recently these entered soil.
- Corrosion pitting was not found to be an important release route for explosives.

GRAPHICAL ABSTRACT

We sampled soils beneath and beside 42 *in situ* unexploded ordnance.



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ABSTRACT

Unexploded ordnance (UXO) become point contamination sources when their casings fail and their explosive fill dissolve. To determine the modes of failure, we documented the condition of UXO found on military training ranges and sampled soils for explosives beneath 42 *in situ* UXO. We found that oxidation caused the metal UXO casings to swell and fail catastrophically. Unlike previous work, pitting of the metal casings was not found to be an important release route for explosives. Of the 42 UXO sampled, eight were leaking explosives into the soil and of these, four had perforated or cracked casings, three were corroded and one was a partially detonated round. We estimated a surface density of 74 UXO per hectare for a subset of UXO sampled. We used the relative concentrations of explosives and their transformation products in the soil to determine if the explosives had recently dissolved or were from past military training.

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1. Introduction

The US military fires explosive-filled munitions during training where they detonate high order, partially detonate, or fail to detonate giving rise to unexploded ordnance (UXO) (Fig. 1). Data compiled on the relative frequency of these outcomes suggest that most rounds detonate high order (Dauphin and Doyle, 2000; Dauphin and Doyle, 2001) and leave very little explosive-containing residue (Hewitt et al., 2003; Jenkins et al., 2006; Walsh et al., 2011a). Partial detonations occur infrequently (Dauphin and Doyle, 2000; Dauphin and Doyle, 2001), but scatter pieces of undetonated explosives and are thought to be the primary source for dissolved explosives in the soil and groundwater (Taylor et al., 2004; Nalbandian and Kalikian, 2007). UXO are rounds that do not detonate and it is estimated that about 3% of fired munitions result in UXO (Dauphin and Doyle, 2000; Dauphin and Doyle, 2001).

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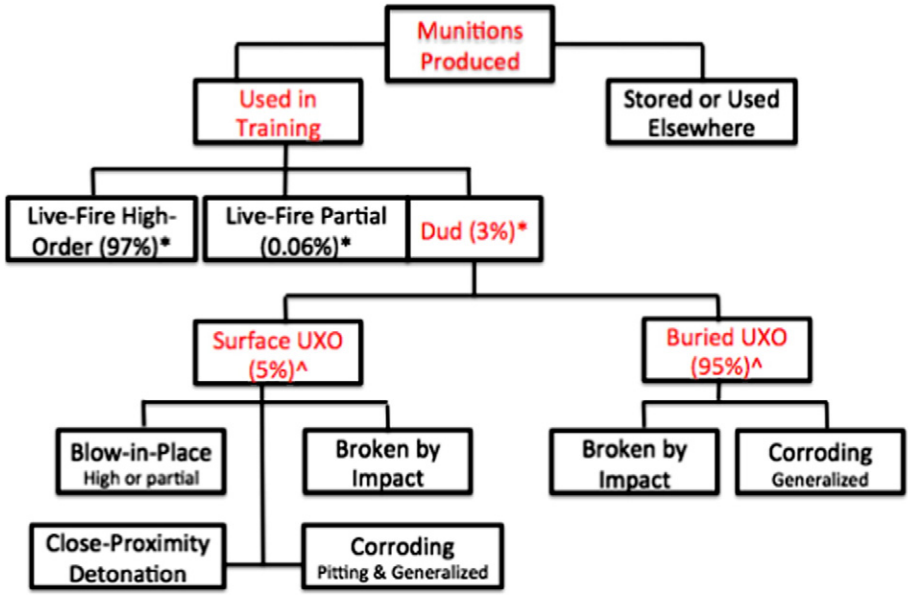

Fig. 1. Possible fates of munitions fired during training. Data are from *(Dauphin and Doyle, 2000; Dauphin and Doyle, 2001) and ^(UXO Recovery Depth Database, n.d.).

Collectively, UXO contain the largest masses of explosives on training ranges and are found at 1500 different sites, encompassing 15 million acres of land (Foster, 1998). As none of their explosive fill has burned or exploded, UXO release 100% of their explosive fill into the environment once their casings fail. Dissolution of explosives and their transport off the military training ranges via groundwater can trigger regulatory action and close the range to training (Clausen et al., 2004).

There are several ways that a UXO casing can fail. If the UXO is buried, it could have broken during impact or corroded. The corrosion rate depends on the thickness and composition of the round, how long the UXO has been in the environment and the soil and climactic conditions at the site (Taylor et al., 2004). If the UXO is on the surface, it can corrode, be perforated by shrapnel by a nearby detonation (Walsh et al., 2011b) or be blown-in-place (successfully or unsuccessfully) by a remediation operation (Fig. 1).

Data on the condition of UXO are limited. Contractors, tasked with blowing up UXO at former ranges, and explosive ordnance disposal technicians usually do not document the condition of the rounds. Existing data are in the “gray literature” that can be difficult to obtain. Although corrosion of metals has been studied [e.g., (Romanoff, 1957; Szklarska-Smialowska, 1986)], how corrosion affects UXO is not well documented (Taylor et al., 2004). One previous study examined 161 UXO, 59 of these were thought to contain high explosives (HE) and soil near four of these had explosives in $\mu g L^{-1}$ quantities (Chendorain et al., 2005). These UXO were not moved and pitting on their exposed surfaces was described as the dominant corrosion process. The pit depths and pit densities measured from these 161 UXO of known age were used to model corrosion rates (Chendorain et al., 2005). The model results showed that the time scales needed to breach the UXO casing via surface pitting were hundreds of years (Chendorain et al., 2005).

The goals of our research were to determine (a) the condition of the UXO, (b) the effects of climate on their condition, (c) the number of UXO leaking high explosives (HE) and (d) the concentrations of HE adjacent to and under these rounds. The condition of UXO is critical for estimating the mass of explosives that can be dissolved in the environment and contaminate of groundwater.

2. Experimental

2.1. Site descriptions

We examined UXO at three military training sites: Eagle River Flats, Alaska; Former Camp San Luis Obispo, California; and Camp Garcia on the island of Vieques, Puerto Rico. The three locations have diverse climate and moisture regimes as evidenced by their long-term precipitation and temperature trends (Supplementary materials SM1).

Anchorage Alaska has a subarctic climate, but strong maritime influences moderate its temperatures. The Alaskan salt marsh we sampled is an active impact area on the Joint Base Elmendorf-Richardson just east of Anchorage. Howitzer, mortar and rocket rounds have been fired into this tidal flat since the mid 1940s. The salt marsh, at about 4.5 m above sea level, may be flooded several times a month. It is a very wet environment, with varying mixtures of saline and fresh water, which should have high rates corrosion.

Former Camp San Luis Obispo, in central California has a Mediterranean climate, characterized by warm to hot, dry summers and mild, wet winters influenced by the North Pacific subtropical high-pressure cell. The camp was formally known as Camp Merriam when established after World War I as a state owned training area for the California National Guard. During World War II, the U.S. Army leased the facility for infantry division training with artillery, small arms, mortar, rocket and grenades (Parsons, 2009). After a period of inactivity, the Army trained at the camp again during the Korean War from 1951 to 1953. Our sampling was conducted within Rifle Range #12 of the Munitions Response Site 05 Range Complex.

Vieques is a small island (34 km long, 6 km wide) in the Caribbean Sea about 20 km southeast of Puerto Rico. It has a tropical climate that is predominantly maritime, with warm temperatures and high humidity. The U.S. Navy used the former Vieques Naval Training Range on the eastern end of the island for ground warfare and amphibious training, naval gunfire support training and air-to-ground training after World War II and until 2003 (CH2MHill, 2007). More information on these sites and the location of the samples is given in the supplementary materials (SM2 to SM4).