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The Archaeology of Unexploded World War II Bomb Sites in the Koźle Basin, Southern Poland

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Abstract

One of the largest territories affected by the aerial bombardment carried out in Europe in 1944 is located near Kędzierzyn-Koźle. Surrounded by former synthetic fuel production plants, it contains craters from the explosions of detonation and general-purpose bombs, as well as smaller craters indicating the existence of unexploded bombs. The research presented in this article was conducted in forested areas and swampy wastelands, where these forms have been preserved until today. The article includes the analysis of their distribution and morphology, as well as characteristic cases occurring in multiple geoenvironmental situations. It also provides a model for research work leading to the determination of the most likely locations of unexploded bombs.

Keywords Bomb craters · Unexploded bombs · LiDAR · Conflict archaeology · World War 2

Introduction

Military conflicts come to an end and become part of history, but their material traces survive. They are the subject of research into conflict archaeology, for instance. Recent years have seen a growing interest in the archaeological value of WW2 relics, including bombing sites. In addition to the widely accepted term "conflict archaeology," the evocative terms "bombscape archaeology" (Passmore et al. 2014) as well as "archaeology of bomb craters" and "cratered landscapes"

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("craterscapes") have emerged (Passmore and Capps-Tunwell 2020). However, the results of such archaeological investigations can also form the basis for utilitarian measures to ensure security.

Unexploded bombs are specific artifacts – objects that threaten people's lives. On many occasions they remind us of events from several decades ago in an unexpected and abrupt manner. On June 24, 2019, at 3:52 a.m. (1:52 GMT), near the central German town of Limburg, a 500-lb (227 kg) bomb dropped in the Second World War (WW2), which was lying in the ground, self-detonated. The crater left after the bomb exploded was 10 m wide and 4 m deep (Bilyeau 2019; Gonzalez 2019). On October 13, 2020, in Świnoujście there was an attempt to neutralize a 5.4-ton bomb dropped in WW2 by means of deflagration. It was located at the bottom of a watercourse leading to the port in Szczecin. One third of the explosive load was burned out, while the rest detonated. The water column ejected from the bottom of the canal reached a height of almost 100 m (Deflagracja Tallboya 2020; Madej 2020). On December 1, 2021, an old aerial bomb exploded during drilling works at a train station in Munich. Four people were seriously injured and there was significant property damage (Halasz and Stern 2021).

The public are often informed about similar cases (Higginbotham 2016) and about casualties from detonations of unexploded bombs (UXBs) (Routine Disposal 2010; WW2 bomb kills 2010). The problem of unexploded ordnance (UXO) is the subject matter of numerous research projects prior to practical activities undertaken to neutralize hazards (i.e., Baum 1999; Brenner et al. 2018; Byrnes 2009; Foley 2008; O'Neill and Fernandez 2009; Shepherd 2016; Spyra and Katzsch 2007). Specialist handbooks (i.e., Bureau of Land Management 2006; Cooper 1996; Tarnowski 1938; US Environmental Protection Agency 2002) and reports (Etter and Delaney 2003) have been issued for many years now. Moreover, conferences on UXO are held followed by the publication of relevant materials (i.e., Byrnes 2009; EUREL 1996; Harmon et al. 2005; Second International Conference 1998). The question of the UXBs themselves has been discussed in fewer scientific studies (i.e., Barone 2019; Gough 1947; Katzsch 2009; Mahling et al. 2013).

Though the problem of UXO and UXBs is taken seriously, in some countries the progress of work on their identification is unsatisfactory for various reasons. Since the end of WW2, examination of this topic has strongly depended on the technical means available to detect different types of ordnance, as well as the financial and equipment resources required when excavating it. Currently, besides the issue of UXB as a threat to people and a barrier to development, it is worth noting that the problem of unexploded ordnance is still rarely addressed in the archaeological literature (i.e., Passmore and Capps-Tunwell 2020; Shepherd 2016; Waga et al. 2022c).

Owing to the explosive potential and, usually, their burial at considerable depth, the identification and neutralization of UXBs represent a particularly difficult challenge for researchers and bomb disposal teams. According to post-war estimates, 5–15% of aerial bombs failed to detonate (Baldoli et al. 2011; Barone 2019; Dolejš et al. 2020b; Katzsch 2009; Kruse et al. 2019; Shepherd 2016); in some cases, even higher indicators of danger are applied during risk assessment (Mahling 2013).

Two types of approach are adopted for research into the spatial distribution of UXBs and the determination of relevant danger zones:

1. Based on the analysis of remote-sensing and cartographic sources, a theoretical level of risk created by the possible presence of unexploded ordnance is determined using statistical methods (Brenner et al. 2018; Foley 2008; Kruse et al. 2019; Lin et al. 2020; Mahling 2013; Mahling et al. 2013; Merler et al. 2005). It is most commonly assumed that the greater the density of craters produced by detonated bombs in a given area, proportionally higher is the threat posed by the existence of unexploded bombs. In addition, the application of advanced automatic and semi-automatic systems of detection of unexploded ordnance is suggested. They involve comparing, using computer programs, oval hollows of specific sizes, identified by scanners (e.g., on aerial or satellite images), with field-verified patterns. The level of human intervention in this process depends on the excellence of graphical-analytical software and its ability for the so-called machine learning on the basis of new data (Brenner et al. 2018; Dolejš et al. 2020a, 2020b; Juhász and Neuberger 2018; Kruse et al. 2019; Mahling 2013; Merler et al. 2005).
2. An active search for undetonated bombs is carried out in areas that were subject to bombing. The first phase primarily involves the analysis of aerial photos from different periods, shaded relief rasters generated from DSM on the basis of LiDAR and images obtained by using other aerial scanning methods. Various algorithms are applied to find minor craters, usually located near large post-explosion craters (Byholm 2017; Meixner and Eckstein 2016). In the second phase noninvasive ground research is conducted with geophysical equipment (i.e., Beard et al. 2004; Butler 2003; ITRC 2004; Jol 2009; Note et al. 2019; O'Neill and Fernandez 2009; Szczepaniak et al. 2010). The depth range of accurate application of various devices and features of geological structure, which hinder the interpretation of deep scanning results, pose a problem for this type of research (Jol 2009; Note et al. 2018; O'Neill and Fernandez 2009; Tang et al. 2018; US Environmental Protection Agency 2002).

In both methods, serving mainly application purposes, the use of historical and archaeological research and the oral testimony of witnesses are valuable (Dolejš et al. 2020b; Konieczny 1998; Shepherd 2016).

The aim of the research described in this article was to determine the amount, morphometry, and distribution of small hollows that may indicate the occurrence of UXBs in extensively used and unutilized areas. This action is intended to provide documentation for conducting a noninvasive ground survey in various environmental conditions in zones where relevant landforms have been identified. The authors conducted statistical analyses of craters, relying on materials derived from LiDAR scanning. They took up actions as part of the second approach, intending to launch a special research project focused on investigating the UXB problem in the Koźle Basin (Waga et al. 2022a). Data from the study carried out to examine areas at risk due to the presence of UXBs constitute the first systematically collected materials in the Koźle Basin area, which was bombed during WW2.

Study Area

The study area lies in southern Poland, within the Racibórz Basin (Gilewska 1999; Kondracki 1994; Szczepankiewicz 1972), also known as the Koźle Basin (Klimek 1972) (Fig. 1). Detailed research was conducted in an area on the floor of the valley of the Odra River, formed in the Vistulian stage, which is built up of fine gravel of 15 mm diameter and silt (Waga 1994). On the surface of a fluvial terrace there is a cover of aeolian sands and dunes. In land depressions there are organic sediments with a thickness of 1–6 m (Schubert and Kurtz 1930; Waga and Fajer 2021). Part of the area is heavily waterlogged. The depth of the groundwater ranges from 0 to 3 m. Such conditions resulted in the development of podzols, peat, and muddy peat soils (OWI – OGIS Portal, http://maps.opolskie.pl/) and therefore the area was left as forest and wasteland.

Detailed research designed to identify the zones at risk from the presence of UXBs near Kędzierzyn-Koźle was conducted in the area of strategic bombardment

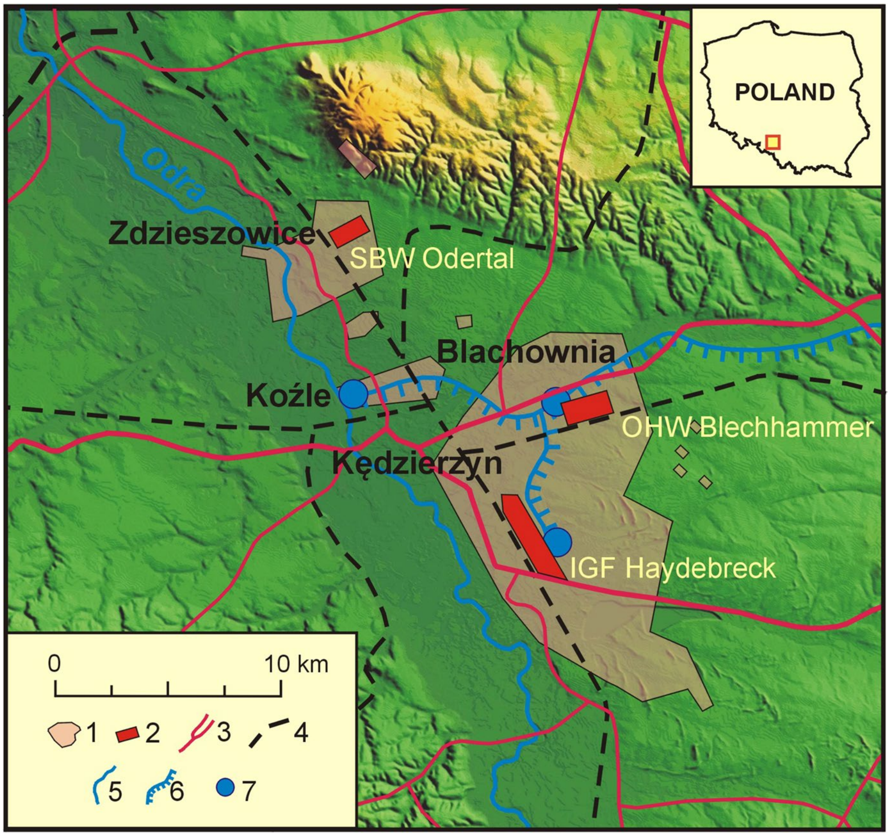


Fig. 1 Location of the study area. 1 – areas bombed in 1944, 2 – former synthetic fuel production plant, 3 – roads, 4 – railway, 5 – river, 6 – canal, 7 – port (Prepared by J. M. Waga and B. Szypuła)

conducted by 15 United States Army Air Forces (USAAF) in the second half of 1944 (Fig. 1). The three study grounds include uninhabited, unutilized, or extensively utilized areas. These are:

1 a paleomeander with paleochannel and meander backwater, partly covered with forest and partly with swampland,
2 the undulating surface of the fluvial terrace with low aeolian forms occupied by tall vegetation,
3 a trough-shaped valley with a swampy bottom, partly covered with reeds and partly with trees.

At the beginning of the 1940s, the southern part of this area was used by a military or militarized unit. The southern part of the area had been specially guarded by military or militarized units since the early 1940s. There were two medium-sized anti-aircraft shelters for several dozen individuals, single-person shelters – *Splitterschutzzelles* – and anti-aircraft artillery positions (Konieczny 1998). Identification of the purpose of the area requires further research. It is probable that this area now has the highest concentration of bomb craters in Poland, totaling over 75 forms/ha (Waga et al. 2022c).

Bombing Remains in the Kędzierzyn-Koźle Area

During WW2, the Germans lacked oil, and therefore they initiated the production of synthetic liquid fuels. The largest fuel-production complex of the Third Reich was established near Kędzierzyn (Ehlers 2009; Haduch 2019; Levine 1992). This consisted of three chemical plants in Odertal (Zdzieszowice), Blechhammer (Blachownia Śląska) and Heydebreck (Kędzierzyn) (see Fig. 1). Owing to technical problems and the effects of bombing conducted by the USAAF, the Germans did not reach the intended production of 730,000 tons of fuel a year (Haduch 2019; Konieczny 1998). During WW2, heavy strategic bombing was the most effective way to destroy the enemy's industrial potential (Levine 1992; Overy 2002).

The bombing of the plants in the Koźle Basin was conducted by American B17 and B24 bombers from July 7, 1944, to December 26, 1944. Nearly 40,000 bombs with RDX payloads were dropped in an area of about 150 km^2 (see Fig. 1) (Konieczny 1998; Waga and Fajer 2021). These were mainly 500 and 250-lb (227 and 113 kg) demolition bombs and 500 and 250-lb (227 and 113 kg) general-purpose bombs. For example, out of 16 raids carried out on the fuel-production complex, 13 involved the chemical works in Heydebreck (Konieczny 1998). In total, 17,688 bombs with an overall weight of 3995.25 t were dropped there. Apart from incendiary bombs, 17,369 cratering (i.e., demolition) bombs and general-purpose bombs were used there (Waga and Fajer 2021).

The indiscriminate use of aerial bombs has significantly altered the geomorphology of the areas near Kędzierzyn-Koźle. There are still large post-explosion craters in the Koźle Basin, the majority probably created by 500-lb (227 kg) bombs. These craters are 8–14 m in diameter and up to 3.0 m deep. In addition there are smaller ones – mostly created by 250-lb (113 kg) bombs, which are 5–9 m in diameter and up to

1.5 m deep, and finally there are small hollows which imply the presence of undetonated bombs (Table 1). In 1944 the wartime German administration recorded cases of unexploded ordnance and established specialist units for their clearance (Konieczny 1998). In the 1940s and 1950s remnants of bombs were removed in industrial areas and settlements, as well as on communication routes, while craters in fields and wastelands were backfilled. Due to their small volume, it was (unfortunately) particularly easy to refill small craters created after the fall of UXO. Nevertheless, unfilled craters of both types have remained in forested areas and wastelands.

During the research into post-explosion craters occurring in the relief of the Kędzierzyn-Koźle area, hollows of 2–3 m in diameter and 1 m deep were identified in higher-located areas, as well as much shallower forms 2–4 m in diameter, which were detected in wetlands. Some of these may be craters produced by UXBs. The study area in great part is swampy and built from waterlogged clastic material (quicksand). Owing to its soft soil, a considerable proportion of the unexploded bombs may be expected in that area.

The above-mentioned environmental conditions are a serious impediment to effective excavation of unexploded ordnance. The major reason is that they require the groundwater, which here forms a very ample aquifer, to be drained from the location of the UXBs prior to excavation. The application of well points for this purpose may prove insufficient, while the use of deep sheet piling to obstruct the inflow of water into the particular unexploded device to be removed is technically demanding, very costly and dangerous – it can trigger an explosion. Such an explosion, owing to its substantial shock force, can lead to the explosion of further UXBs located nearby as part of a chain reaction or snowball effect (comp. Liu et al. 2019). All the above are arguments for excluding at least some of these areas from heavy economic use. If a decision is made to clear a site of UXBs, it is necessary to precisely locate unexploded ordnance, conduct a thorough ground-hydrogeological examination and risk assessment and designate buffer zones.

Working Methods and Materials

In the first, small-scale phase of the research shaded relief rasters generated from a DTM model of 1 × 1 m resolution were analyzed in the Geoportal of Open Spatial Data (http://polska.e-mapa.net) and areas including hollows of 2, 3, and 4 m in diameter were selected. Next, high resolution digital terrain models of 0.1 × 0.1 m and 0.05 × 0.05 m resolution were created for these areas. Point clouds in the *.las file type (according to ASPRS, 2008 standard) derived from airborne laser scanning (ALS) at a minimal density of 12 points/m2 and mean vertical accuracy < 0.1 m were used for that purpose. The ALS data were obtained with a Leica ALS70 scanner on April 9, 2019. All the data were created in the EPSG:2180 coordinate system. Digital elevation model was created based on *.las files from which Class 2 (ground) and Class 9 (water) from the first and second returns were selected. Global Mapper (2018) software with default settings was applied (create an elevation grid to be used in the analysis – binning, minimum value – DTM). Binning is a data processing technique that takes point data and creates a grid of polygons, while an

Table 1 Numerical description of study structures and areas

Area No		1	2	3	Total
Area in ha (km^2)		57.0 (0.57)	30.4 (0.304)	8.8 (0.088)	97.0 (0.97)
Number of post-explosion craters		166	306	313	785
Number of UXB with a 5, 10, and 15 – percent share of unexploded ordnance in drops[1]		8.7/18.4/29.3	16.1/34.0/54.0	16.5/35.2/55.9	41.3/87.2/138.5
Number of oval hollows with a diameter or longer axis of 1–4 m, determined on the basis of small-scale research and a field study	Hollows of different origins – in total	134	146	123	403
	Pits and hollows after removal of trees	26	77	39	142
	Zoogenic hollows	35	10	1	46
	Excavations after mining of mineral resources	0	2	0	2
	Excavations resulting from economic activity (including those in forests)	6	2	0	8
	Excavations after building and repair works	4	0	2	6
	Hollows after removal of elements of infrastructure	0	0	12	12
	Trenches, shelters, and similar military structures	1	1	3	5
	Craters after gunfire and exploded mines	0	2	0	2
	Craters probably produced by fallen UXBs	21	14	11	46
	Hollows of unclear or complex origin	41	38	55	134

1) calculated according to the formulas: NUXB 5%= NBC X 100/95 – NC, NUXB 10%= NBC X 100/90 – NC, and NUXB 15%= NBC X 100/85 – NC, where: NUXB– number of craters with UXB, NC – number of post–explosion craters, NBC number of all craters (NBC =NC increased by 5, 10 or 15%)

Source: authors' own study

inverse weighted distance algorithm is used to fill in the gaps. These models were used to generate shaded relief rasters of the same resolution as the source models (i.e., 0.10 × 0.10 m and 0.05 × 0.05 m) and with standard lighting configuration (azimuth 315°, altitude 45°). The materials prepared in such a way provided the basis for conducting detailed analyses of the distribution and morphology of potential UXB craters. The forms thus identified were classified into three groups, depending on the different probabilities of their genesis being connected with falling bombs (1– highly probable, 2 – uncertain, 3 – unrelated).

While conducting the analyses, the location of craters in relation to the directions (axes) of raids was taken into consideration. The number of craters in a group (sequence, series) was counted, assuming that, owing to the range of the bombers, bomb drops in this area most often consisted of 8 × 500 lb (227 kg) or 16 × 250 lb (113 kg). If there were no big craters in the group examined, small craters with unexploded ordnance were searched for in the vicinity. However, the analysis model of 8/16 bomb drops could not always be applied. In severe winter weather conditions, the payload was reduced from 4000 lb (1814 kg) to 3000–3500 lb –(1361–1588 kg) and 1–2 bombs were dropped on substitute targets, sometimes even just after takeoff, before reaching the Koźle Basin (The Fifteenth Air Force, https://15thaf.org). It was not the only aspect preventing the application of this method. Another reason was the sequential character of bomb drops in certain zones and also overprinting from multiple raids. In such locations groups of craters overlapped and it was impossible to separate them. In every case the relationships of craters to similar forms and the references to other elements of the landscape were analyzed. Moreover, an orthophotomap was drawn up for open areas (not occupied by dense vegetation). The data were obtained from DJI Mavic 2 Pro drone flights carried out in November 2020. The flight altitude was 50 m using a Hasselblad camera, L1D-20c, 1/400 s shutter speed at ISO 200. The flight lasted about 6 min and during that time 89 pictures were taken with a 2.03 × 2.03 cm pixel.

The data were then processed in AgiSoft MetaShape Professional (2020) software. Routinely, after loading the photos and creating Align Photos, a dense cloud was built on the basis of which a digital surface model (DSM) and orthomosaic were generated. The final stage was to Classify Ground Points to eventually achieve a digital elevation model (DEM). The simplest method of creating elevation models and an orthomosaic (i.e., processing the aerial data without ground control points (GCPs)) was selected. The final resolution of the orthomosaic was 1.4 × 1.4 cm, while the resolution of the digital elevation model was 2.8 × 2.8 cm. A Kernel Density device with default settings in ArcGIS (2020) software was used for calculating the density of craters in the study area.

The forms chosen for further detailed research were located in the area with a GPSMAP 66S receiver and they were subsequently measured with a Nikon Forestry Pro II laser rangefinder and geodetic methods. Geological conditions were identified on crater slopes, as well as adjacent hollows and excavations. Surface ground and soil conditions were examined with a 1-m sampling stick.

Additionally, to determine the environmental conditions and the historical background of the research polygons, analyses of the content of 1:50,000 geological, sozological (i.e., environmental conditions) and hydrographic maps were performed, as well as of a soil map from OWI – OGIS Portal (http://maps.opolskie.

pl) and of information from the CBDG (Centralna Baza Danych Geologicznych) (CBDG, http://baza.pgi.gov.pl/). Analysis was made of archival mission reports, publications published on the AFHRA (Air Force Historical Research Agency) website (https://www.afhra.af.mil), material in the National Archives (https://www.archives.gov) and The Fifteenth Air Force (https://15thaf.org/), as well as scientific literature on the allied air offensive against the Third Reich and websites of associations documenting warfare in Silesia and its material remnants, including, most of all, those of the "BLECHHAMMER – 1944" Association.

Identification of Hollows Produced by UXBs

In the area of the Koźle Basin under study, which was bombed in 1944 and did not undergo land rehabilitation (i.e., forested areas, some meadows, pastures, wastelands and "abandoned" formerly utilized areas) there are numerous oval hollows of 1–4 m in diameter. They have a similar shape, diameter and in certain conditions also depth to craters created after the fall of unexploded aerial bombs. Some of these are certainly craters created by UXBs. The initial division of forms into different origins was performed from shaded relief rasters of varied resolution. Then their features were verified by field study. These include forms most probably originating from UXBs. The places where UXBs fell could not be unambiguously identified within craters located in waterlogged areas, and currently permanently filled with water. However, in shaded relief rasters there are oval hollows implying the existence of UXBs.

Magnini et al. (2017) point out that holes appearing during deforestation, hollows after charcoal burning, ice-storage pits, and other features have similar sizes to craters of military origin. In order to distinguish the former from explosion-induced craters, they conducted a field study of over 100 shell holes determining their morphometric parameters and morphological features. They also claimed that "Remains of charcoal mounds are also flat but … only 20–30 cm deep, while ice-storage pits can reach 2 m or even 3 m in depth. Deforestation holes are similar to shell craters in size, but they present a soil discharge (which is usually located downhill) created during the uprooting of the stumps. Conversely, shell craters have a perimetric ridge produced by the displacement of ground material during the explosion, but in this case the rim is relatively concentric and uniform in width" (Magnini et al. 2017:215).

Craters created by UXBs in areas utilized in the past can be imitated by partly filled wells, farm cellars, former stock and cesspits, excavations remaining from unfinished structures, underground shelters, removed flagpoles, supporting poles from observation and anti-aircraft defense towers, as well as antenna, energy, telephone and fence towers (this involves all high fences abandoned in the post-war period – former military units or warehouses or concentration camps), sewer manholes, *kochbunkier* shelters (pillboxes) and ornamental species of tree that have been dug-up. In forests these are fallen trees, hollows after charcoal mounds, and pits for collecting pine tar located in the vicinity (Rutkiewicz and Malik 2019), dugouts for storing seedlings, feed for wild animals and equipment for forest works, voids created by the working of aggregates (in this area – sand or sand and gravel) and also, like in open areas, major infantry posts for firing in the standing position (e.g., light machine gun, heavy machine gun) (Breno et al. 2017; Passmore and Harrison 2008). There are also hollows connected with the failure and repair of underground infrastructure systems (e.g., water drains). In waterlogged areas, zoogenic hollows are particularly numerous – wild boar rooting and wallow basins.

For these reasons it is necessary to analyze the diagnostic properties of hollows (de Matos-Machado et al. 2019). Apart from their dimensions, the first feature indicating the post-drop origin of the form is its circular or at least oval shape in plan view. The second one – in dry areas – its initially relatively narrow bottom because, unlike in the case of post-explosion craters, no ejected material falls back inside them. Thirdly – the relatively steep original slopes, inclined at an angle of 30–56º, depending on the type of soil (grain size and dampness, among other things) that the unexploded bomb fell onto (comp. Katsuragi 2016) and what kind of vegetation it was covered with (the density of the root system is important). This resulted from the fact that the root system preserved the edge of the crater both at the time the bomb fell and later. In this case, apart from the shape of the bottom, the secondary geomorphological processes which occur there should also be considered. If an UXB fell in a damp area, then the crater quickly filled with water, as well as there being plasticized and fluidized material from the adjacent ground up to a certain height (Fig. 2). After the creation of such a water reservoir, there was a secondary accumulation of both autochthonous biological material and allochthonous material, deposited, for example, during a flood, lying over the original filling.

Moreover, the phenomenon of so-called bomb drift should also be taken into consideration (Katzsch 2009). Simplified patterns of bomb migration in the ground are presented in Fig. 2. In reality, these paths, like the manner of embedding of unexploded ordnance, vary depending on the angle at which bombs fall on the ground or on the existence of hard or flexible obstacles which may change the course of their movement (obstacles located above ground, on the surface and in the ground). It also involves the impact of local variation in soil density.

The Analysis of Forms in Study Sites

Several groups of hollows were distinguished that correspond to the size of craters produced by the fall of an UXB. These lie in three sites. Their thorough identification will provide the opportunity to reduce the number of structures which should undergo geophysical examination. Nevertheless, some forms whose origin is not fall-related, but which suggest a connection with UXBs, should also be studied in detail. Some of these hollows were compared to similar forms emerging today in the study area, while others were identified on the basis of an analysis of the spatial arrangements of buildings of former farms (i.e. Niedźwiecka-Filipiak 2009), oral accounts of local residents, administrative staff of the state forests and local historians.

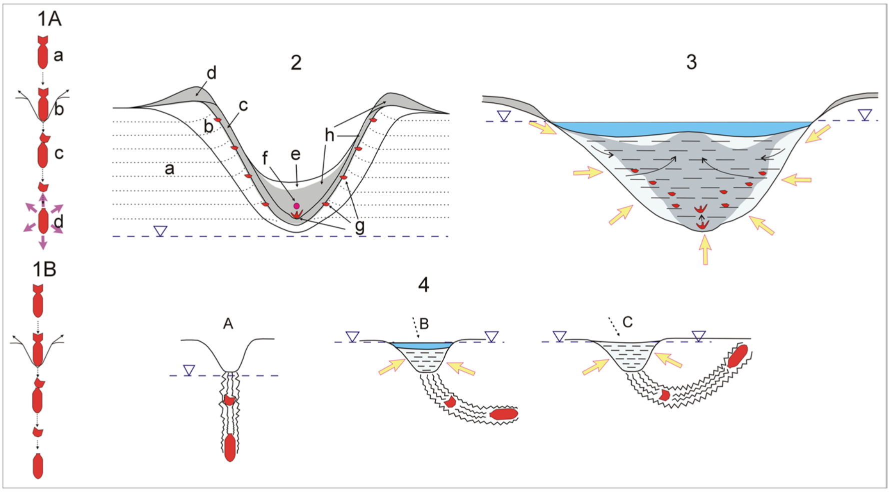


Fig. 2 Bomb crater cross-sections. 1A – bomb track in the ground terminating with an explosion, 1B – bomb track in the ground not terminating in an explosion, 2 – cross-section of a crater created above groundwater level: a – undisturbed ground layers, b – crooked ground layers in the plastic zone, c – material in the rupture zone, d – ejecta, e – fallback, f – center of energy release, g – bomb shrapnel, h – "chemical trace" of the explosion; 3 – cross-section of a crater created in a waterlogged area and occupied by a pond; the arrows indicate the direction of pressing quicksand in the vicinity of the crater and the migration of liquefied material near the crater following the explosion; 4 – UXB post-fall craters: A – in dry ground, B – in waterlogged ground – crater partially filled with sediment and water, C – crater filled with sediment, B and C – UXB after the fall experienced "drifting" (Prepared by J. M. Waga after Cooper 1996 and Katzsch 2009)

Hollows After Fallen and Removed Trees

This area abounds in tree-throw hollows owing to the existence of a shallow water table and the horizontal development of tree root systems. On numerous occasions they are arranged in groups along the course of a strong gust of wind. They have a similar orientation of longer axes – perpendicular to the direction that the wind blew from (Fig. 3). The hollows of this type are usually several dozen centimeters deep and are round, oval or semi-circular – which reflects the range of thicker roots resistant to being broken by wind pressure (Fig. 4A). For a time, the stump of the fallen tree remains displaced, with the ring ("plate") of the root system standing in a vertical position.

The final shape of the pit depends on the foresters' policy on handling cut off rootstocks. With a slight deflection of the rootstock and cutting off of the stump, it returns to the pit, leaving no trace of a hollow in a shaded relief raster. In some cases, stable rootstocks are left with the root "plate" in the vertical position, others are removed together with the stump – which in the course of years impedes the determination of the origin of such a round hollow. In the majority of cases, however, one can see an untouched ground structure in the uncovered bottom of a usually shallow pit. Visible hollows also emerge in locations where very large trees are cut down and their rootstock is mechanically removed. There are also cases of holes

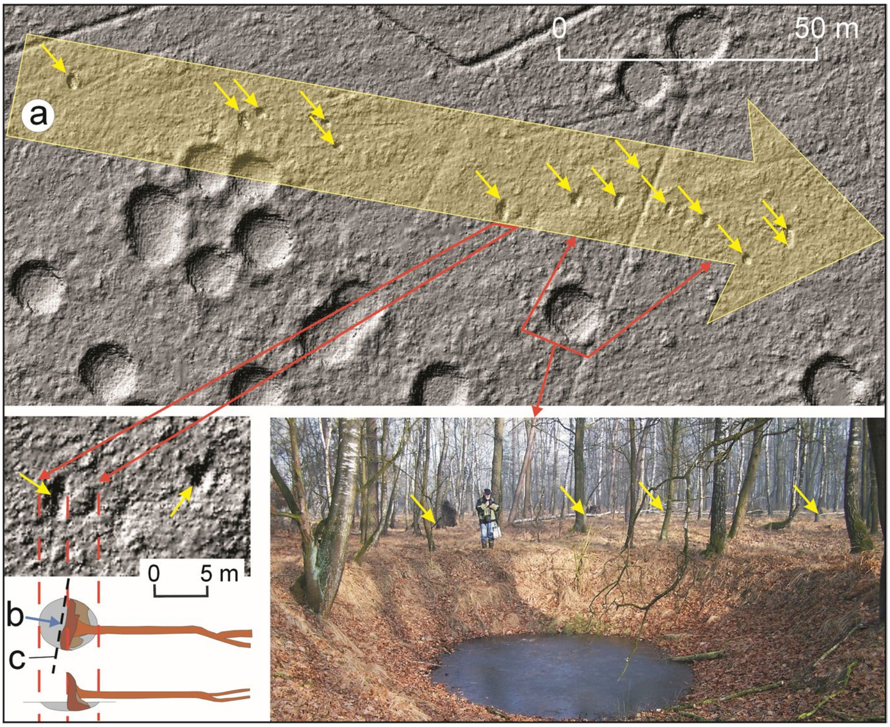


Fig. 3 Tree-throw hollows in bombed areas: a – study area including the course of a strong gust of wind (small yellow arrows indicate tree-throw hollows), b – wind direction, c – longer pit axis (Prepared by J. M. Waga and B. Szypuła)

appearing after the removal of valuable, larger dendrological specimens from former and still-developed farm, housing or recreational areas (e.g., from areas adjacent to forester's houses, from designated green areas – parks, avenues, squares.)

Zoogenic Hollows

Forest animals dig in the ground in search of grubs (frequently reaching a depth of 1 m) up to 3–4 m around dying trees and old rootstocks (Fig. 4B). Wild boars are the most effective animals in such penetration of the ground and in digging around decayed tree stumps or roots. Moreover, they create the largest hollow forms.

Badgers and foxes build setts and earths in places that occupy raised ground (e.g., in dunes) often in the vicinity of bomb craters and on their slopes (Fig. 4C). Owing to the fact that their walls shed material, some entrances to these underground refuges are located in relatively deep holes. Additionally, some of them have also collapsed. This creates hollows that are as much as 0.8 m deep and 1.5 m in diameter.

In waterlogged areas, the majority of which are covered with reeds, there are a large number of zoogenic hollows. They include, most frequently, shallow hollows beaten at the crossing of two or more animal migration paths (Fig. 4D) or hollows

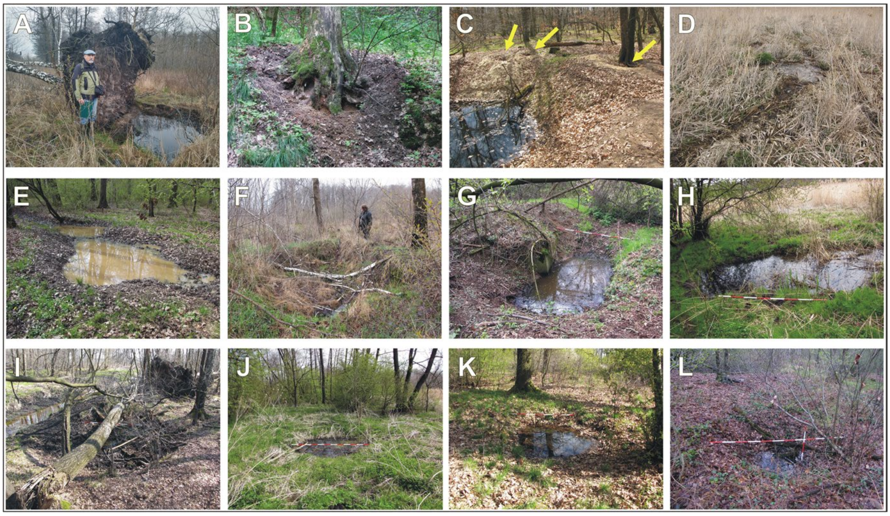


Fig. 4 Examples of hollow features examined in the study. **A** tree-throw hollow, **B** hole dug in the ground around a dying tree, **C** animal 'dens' located near a bomb crater, **D** shallow hollow produced at the crossing of two animal migration paths, **E** wallows, **F** hollow after excavation in forest, **G** and **H** excavations connected with the repair of water drainage structures, **I**-**L** craters probably resulting from fallen UXBs (Photos: J. M Waga and M. Fajer)

of another origin subsequently transformed into wallows by animals (Figs. 4E and 5). The observations made by the authors show that the wild boar is the key species creating such forms. It was confirmed that the amount of active and former, currently overgrown wallows greatly exceeds the potential number of UXB craters. This hinders the identification of drop sites of unexploded ordnance in waterlogged areas.

Aggregate Voids

The exploitation of aggregates in the study area was well organized and usually conducted in larger pits located within dunes (sand) and at the edge of the fluvial terrace (sand and gravel). The material was only intermittently collected near roads, most likely for their repair (Fig. 6).

Farm Excavations

In agricultural areas, usually at the back of farmhouses, there were clamps intended for the winter preservation of root veg and silage for animals. Homesteads also included wells, while farm cellars contained liquid manure tanks – either lined or not and cesspits were located around their edge (Fig. 6). Their outline was initially rectangular, however, after wartime damage and years of geomorphological processes this shape is not always clear. In forests such forms include hollows after

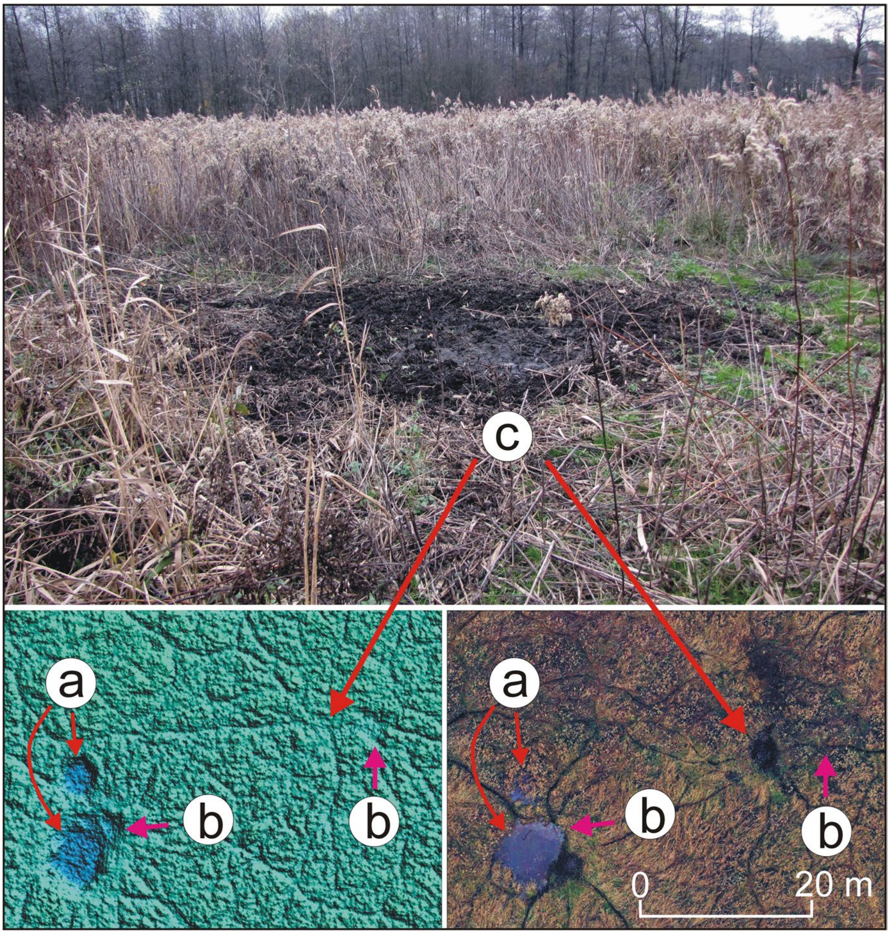


Fig. 5 Fragment of a swampy area; a – craters after bomb explosions, b – presumed sites of fallen UXBs, c – wallow site (Prepared by J. M. Waga and B. Szypuła)

excavations for storing seedlings, feed for wild animals and equipment for forest works (see Figs. 4F and 6).

Excavations for Building and Repair Work

In zones of former development there are excavations following demolition or due to unfinished structures. The origin of excavations and their destination can be inferred from their spatial arrangement in relation to preserved buildings or their remains. There are also hollows along lines of underground infrastructure, mainly water drains. These include, inter alia, wash-outs created as a result of failures and excavations connected with their repair (see Fig. 4G, H). It cannot be excluded, however,

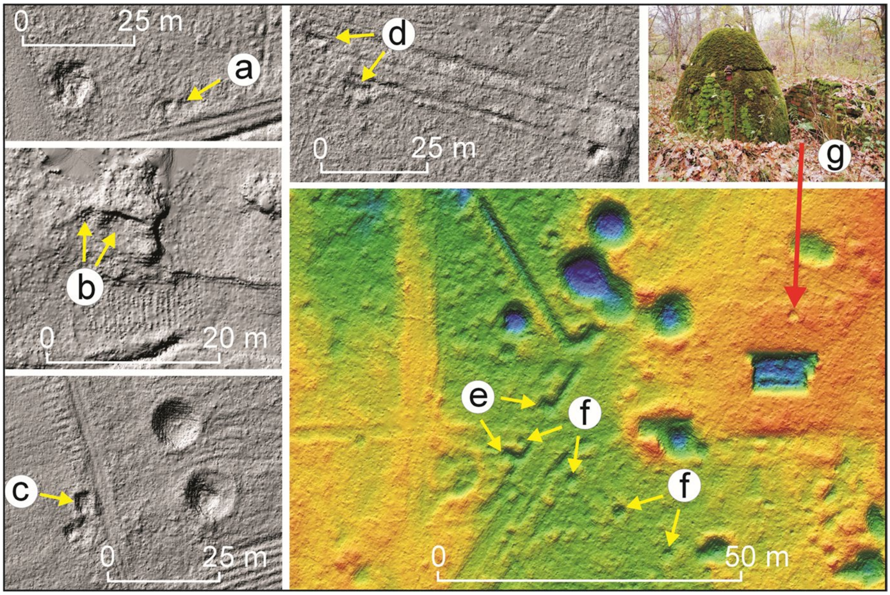


Fig. 6 Examples of hollows imitating UXB craters: a – presumed sand excavation site, b – liquid manure tanks and cesspits, c – hollows after farming excavations in a forest, d – excavations after the failure and repair of the underground infrastructure systems, e – excavations after buildings, f – excavations after posts have been removed, presumed to be an overhead line, g – descent into a kochbunkier shelter (pillbox) (Prepared by J. M. Waga and B. Szypuła)

that certain hollows occurring along lines of infrastructure may originate from shells exploding or fallen UXBs (see Fig. 6).

Hollows after Elements of Infrastructure Have Been Removed

In a formerly specially guarded zone within the study area, a large number of funnel-shaped hollows were identified after posts of various types had been removed. Owing the deficit of building materials, the posts, in the same way as concrete road and pavement blocks, sewer manholes, sewage tank lids and floor drains, were used as materials to reconstruct other facilities after the war. Interestingly, there are, for example, hollows in series, located 10 m away from one another, which indicate that supports were placed there, probably for some overhead line (Fig. 6). It was assumed that if similar hollows appear in a regular pattern, in a straight line, they may be associated with elements of infrastructure lines or fencing.

Trenches, Shelters, and Similar Military Structures

In the same research area, near the above-mentioned series of pits linked to former posts, behind a walled tank basin or the remnants of a basement, there is a hollow leading down to a *kochbunkier* shelter (pillbox) (see Fig. 6). This hollow corresponds to the size of a post-bomb impact crater in a shaded relief raster.

Small shelters of different construction, in the majority underground ones, were built by civilians during the war before the arrival of the battlefront and also next to farms. In addition, at this stage of military activities, the army erected firing posts which the infantry could use in the standing position (e.g., light machine gun, heavy machine gun) frequently on the edge of forests and within elevated areas within fields (Fig. 7). Sometimes older bomb craters were used to build fortifications (Waga and Fajer 2021; Waga et al. 2022c). In many places there were smoke release posts for anti-aircraft screens and interim shelters for their operators. The dimensions of all these remains are similar to impact craters for UXBs.

Craters after the Explosions of Shells and Mines

Craters created by artillery fire mainly occurred within German defense positions and in the immediate forefield. One such zone is located on the eastern slope of a line of dunes (Fig. 7). Some of the small craters may also originate from Russian aerial bombardment with small caliber shells. Additionally, craters which emerged after the explosion of anti-tank mines have the same size as UXB impact remains. However, without the analysis of tactical maps, it is difficult to indicate places where they could have exploded.

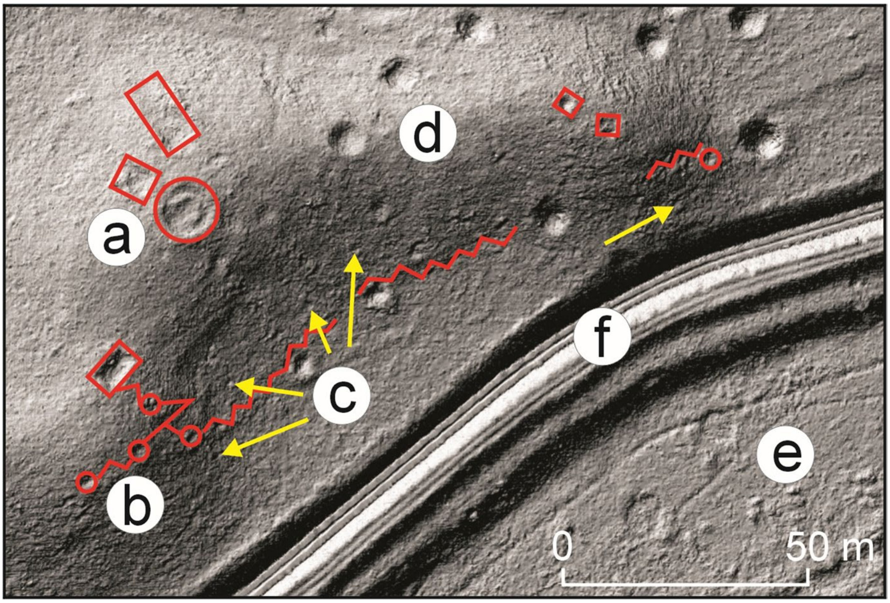


Fig. 7 Examples of hollows imitating UXB craters: a – FLAK position with adjacent shelters, b – shooting positions (light and heavy machine guns) and trenches, c – presumed craters resulting from gunfire. Elements of relief: d – dune, e – valley bottom, f – water canal with an embankment (Prepared by J. M. Waga and B. Szypuła)

Craters after UXBs Have Fallen

During small-scale research and a field study, a group of structures was distinguished fulfilling the criteria typical of craters created by the impact of UXBs (see Fig. 4I-L). They are close to craters produced by bombs which detonated (see Fig. 5) or occur in a group composed of similar structures (Fig. 8). The second case usually involves waterlogged areas, in particular those covered with organic sediment of significant thickness.

The analysis regarding the likelihood of the existence of UXBs was conducted in the study sites examined. This was compared with the number of craters created by bomb explosions examined using shaded relief rasters generated from DSMs on the basis of LiDAR. The results were counted for the indicators of 5%, 10% and 15% and are presented in Table 1. During the site visits, 403 depressions roughly corresponding to the form and dimensions of UXB impact-generated craters were distinguished in the study area. Among these there were 223 forms which did not originate from a bomb impact, 46 forms with a high probability of a certain connection with an UXB and 134 with a lower likelihood. Such cases were verified during field research. Consequently, 180 structures were selected for further study using geophysical methods.

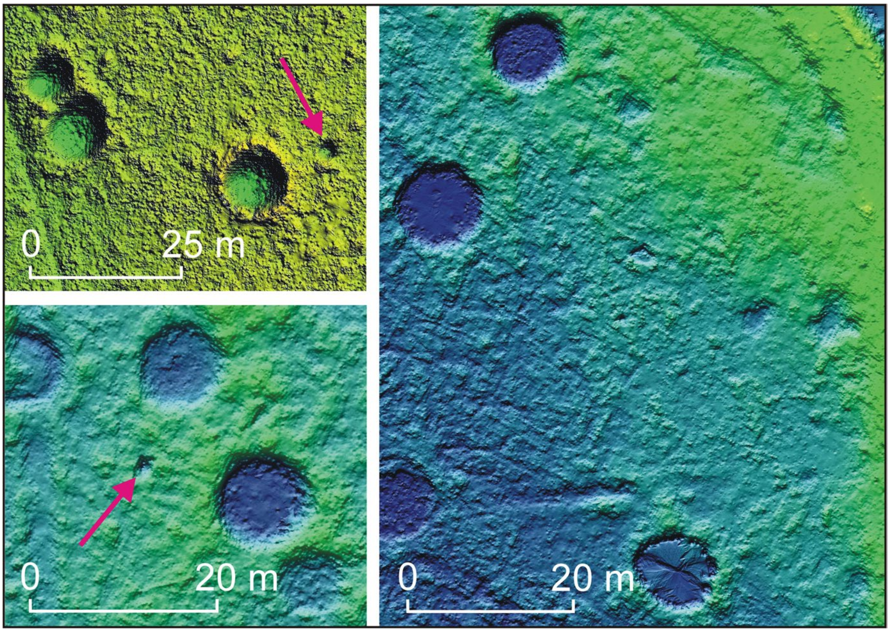


Fig. 8 Areas with presumed UXB craters (Prepared by B. Szypuła)

Discussion

It has been 75 years since the fuel plant in the Koźle Basin was bombed. Most bomb craters in this area have been backfilled and flattened. Events in Great Britain (Unexploded bombs 2018), France (Cohen 2018; Inventaire des déchets de guerre 2014; Thousands evacuated 2014), the Netherlands (Hignett 2019; Kreijger 2012), Belgium (Galindo 2020; Mustermann 2017), the Czech Republic (Dolejš et al. 2020b), Italy (Barone 2019; Biografia di una Bomba 2021; Shepherd 2016) and numerous German cities (Crossland 2008; Mahling et al. 2013) indicate that many unexploded bombs remain in the ground. There are frequent reports of UXBs in Poland (Pulkowski 2020; Walor 2012). There are also accounts of the deadly consequences of their explosions (WW2 bomb blast 2014; WWII bomb kills 2010). Some of the fuzes of these bombs are completely inoperative (due to secondary geoenvironmental processes and other factors), but it is not known how many fuzes can work and in which bombs. That is why it is so important to have a complete picture of the distribution of UXBs. The study of conflict archaeology may prove important in this regard (comp. Barone 2019).

Surveys conducted in urban areas in the Czech Republic show that UXB craters have been preserved there, despite major relief transformations. The use of high-precision aerial terrain models (DTM) LiDAR allowed to determine the exact location of such craters in 84% cases (Dolejś et al. 2020b).

Passmore and Capps-Tunwell (2020) draw attention to the diagnostic features of craters with WW2 UXBs that have been established during military analyses (Foley 2008), while Passmore and Capps-Tunwell (2020) indicate the methods of identifying them remotely. In their opinion, the diameters of such craters should be about 1–3 m.

On contact with the ground, the UXB usually forms a hollow known as a “false crater.” UXB crater has a relatively straight rim and does not have a “lip” of loose soil piled around the edge of the hollow, typical for a post-explosion crater. Natural processes – geomorphological and biological – may have “softened” the crater’s straight edges over time. Craters created in dry soil look different from those in waterlogged areas. In craters located in waterlogged areas ground structures are remodeled and matter from the adjacent area is transported (flowed) into the craters. Craters created by the fall of unexploded aerial bombs (UXBs) should be free from shrapnel unless there were previous explosions in this location. Once the soil is removed from inside the crater, the hole of entry should be exposed. The diameter of the UXB hole of entry (for GP bombs 500 lb; 227 kg) is 0.35–0.45 m (Surface Explosive Ordnance Disposal 1961). According to the same source, UXBs weighing 2,000 lb (907 kg) when they enter the ground can create a crater more than 3 m in diameter and 1.5 m in depth. The depth of penetration of a UXB depends on the type of soil and the weight of the bomb, for example, in wet clay soil, a 500 lb (227 kg) GP UXB penetrates to an average depth of 4.5 m, and the subsequent horizontal drift in soil averages 1.5 m (Surface Explosive Ordnance Disposal 1961). Nearly doubled values of these depths are reported by the authors of the UXO risk assessment report (M25 junction 28 improvement scheme 2020).

The most advanced and comprehensive study on UXBs, including major scientific projects, has been performed for Oranienburg (Katzsch 2009; Spyra 2011). In Oranienburg, which was heavily bombed during WW2 due to, among other things, the existence of laboratories and a uranium enrichment plant at that time, as well as the Heinkel Aircraft Works, the city grounds have been examined and cleared of unexploded aerial ordnance as needed in a systematic and planned manner for many years. The results of this work, although serving primarily applied purposes, are an important source of archaeological and historical knowledge. These activities serve as a model of how to deal with UXBs.

In his work, Katzsch (2009) included information on the depth and manner of placement of the WW2 bombs found in Oranienburg. This is significant owing to the similarity of the raid parameters, as well as the geological and hydrogeological conditions in the areas of Oranienburg and Kędzierzyn-Koźle. The author specified the range of 500 lb (227 kg) bombs falling in various quaternary structures in Oranienburg: in sand and river gravel – 1.1–7.0 m (25 bombs), in peat – 1.5–7.25 m (23 bombs), in quicksand – 4.6 m (1 bomb), in the ground of a man-made embankment – 5.0 m (1 bomb). He also drew attention to the influence of friction and the impact of the shape (leanness) of a bomb on its ability to penetrate the soil, and the so-called problem of bomb drift (i.e., their relocation from the place they entered the ground, most often along an arched course in relation to the ground surface). Many shallowly-buried bombs in that location were affected by the process of long drift. In Oranienburg the average distance of a bomb location was as much as 12 m away from the fall site. However, he sees identifying the locations of soil penetration by UXBs as a key problem. In non-reclaimed areas, the opportunity to do so is provided by an analysis of the relief morphology.

The authors call for systematic activities to be undertaken in the Koźle Basin area, similar to those carried out in Oranienburg (Waga et al. 2022a). Archaeological research on the identification of UXB deposition locations can be carried out complementarily with studies conducted for urban planning purposes.

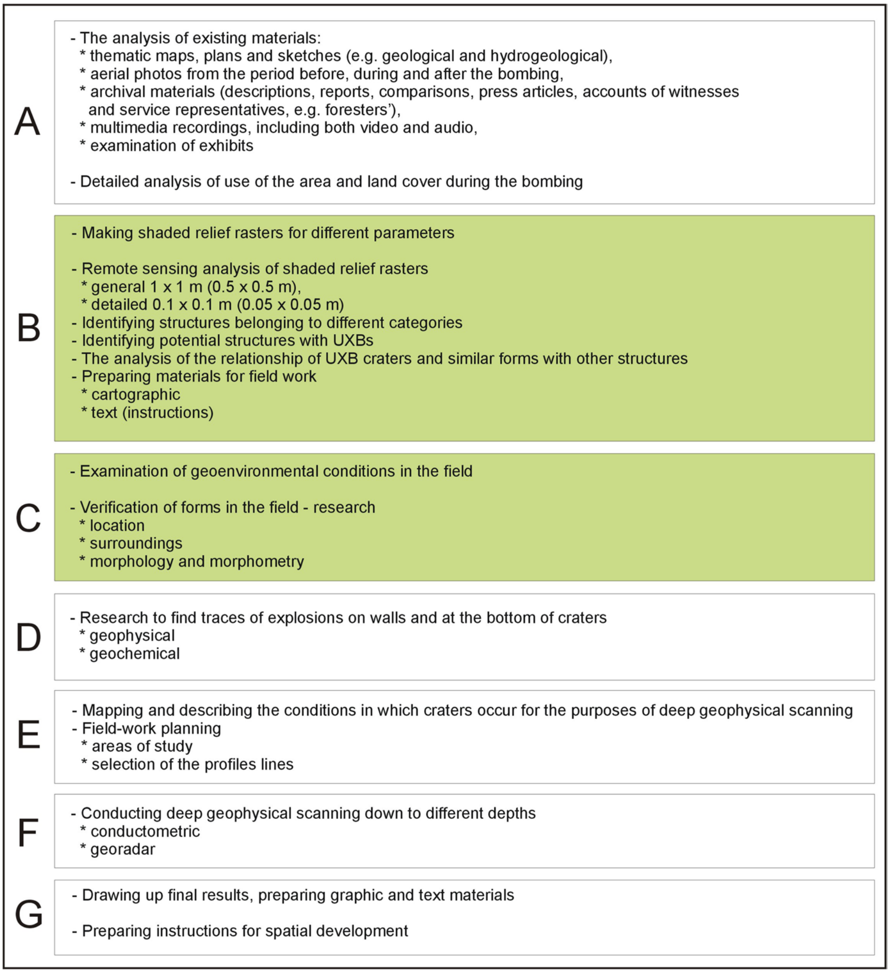
For similarly bombed areas, Mahling (2013) suggested designating three concentric zones surrounding the sites with the largest concentration of bomb craters. In the zones with potential unexploded bombs, one should indicate the existence of various risk levels: from very high (zone with a 50 m radius), through medium (zone with a 100 m radius) to a relatively lower one (zone with a 150 m radius). Where chemical fuzes were used in bombs, these zones are extended up to 300 m. They should be adequately incorporated in spatial development plans and the level of risk for the existing facilities and users should be considered. In Germany, in areas affected by bombing, up to 50% of identified unexploded ordnance was located within such zones (Katzsch 2009). They also specified the features of areas which belong to five special hazard classes. For the fifth (the highest danger) class, he listed the following parameters: very great likelihood of the existence of chemical fuzes, high density of craters (>750 per km2) and the occurrence of sites where unexploded ordnance is expected (>300 per km^2). It can be noticed that one of the features determining inclusion into the highest hazard group is a density of post-explosion craters which exceeds 7.5 craters per hectare (750 craters per km^2). In one study area the ratio achieved was as many as 77 craters per hectare (7700 craters per km2) in one location!

According to the authors, such areas, if there are no particularly compelling reasons for investment in these particular locations, should be left as protection zones for: landscapes shaped by military activities, post-military landforms, military structures, self-restoring natural complexes, research sites for landscapes of war conflicts and "troublesome" historical remnants resting in the ground (Waga and Fajer 2021; Waga et al. 2022a, 2022b, 2022d). This is supported by historical, natural, technical, and economic considerations. It will also avoid the risk of accidental UXB explosions.

This article presents the situations in three selected unreclaimed sites near Kędzierzyn-Koźle with clearly visible ground surface features indicating the existence of UXBs. For the purpose of research, but also for spatial planning decisions, it is a more advantageous position than in the case of reclaimed or economically developed areas, which require a more complex analytical process, providing less reliable results in the end (comp. Katzsch (2009)—32–70% efficiency in identifying found and excavated UXBs). The process of identifying UXB fall sites can be conducted in a twin-track approach: separately for untreated and reclaimed areas, as presented in the diagram in Fig. 9. In the first case, which has been discussed in this article, the initial step contained an analysis of aerial laser scanning data and consider other data as a support. In the second case, it is necessary to go through the entire cycle – from the analysis of heterochronous aerial photos (mainly stereoscopic) and archival documentation of the subject to the phase of preparing input data for scanning with the application of geophysical methods. Similar action schemes have been presented in numerous guidebooks and guidelines presenting various types of unexploded ordnance (ITRC 2004), among others). Subsequent steps taken by the authors will consist of deep conductometric and magnetometric land profiling.

Traces of past wars, including bombing craters, are considered a negative legacy in many countries (Hesse 2014). However, they have special historical value. Such heritage military landscapes also have archaeological value (i.e. Dolejś et al. 2020b; Kajda and Kobiałka 2017; Kobiałka 2017; Passmore and Capps-Tunwell 2020). From the perspective of archaeology, in an era of intense economic development and construction activity, the issue of treating bomb craters (in particular their numerous clusters) as landscape heritage, but also UXB as dangerous heritage hidden in the ground, becomes relevant.

Analyses of the remnants of military activities, including the presence of UXB, against the backdrop of landscape changes, in many cases have a strong impact on public awareness (Kajda and Kobiałka 2017). This includes not only the promotion of historical and archaeological knowledge, but also the practical dimension of archaeological research. Herein, the study of conflict archaeology can go beyond social science and support applied sciences.



A

- The analysis of existing materials:
  - * thematic maps, plans and sketches (e.g. geological and hydrogeological),
  - * aerial photos from the period before, during and after the bombing,
  - * archival materials (descriptions, reports, comparisons, press articles, accounts of witnesses and service representatives, e.g. foresters'),
  - * multimedia recordings, including both video and audio,
  - * examination of exhibits
- Detailed analysis of use of the area and land cover during the bombing

B

- Making shaded relief rasters for different parameters
- Remote sensing analysis of shaded relief rasters
  - * general 1 x 1 m (0.5 x 0.5 m),
  - * detailed 0.1 x 0.1 m (0.05 x 0.05 m)
- Identifying structures belonging to different categories
- Identifying potential structures with UXBs
- The analysis of the relationship of UXB craters and similar forms with other structures
- Preparing materials for field work
  - * cartographic
  - * text (instructions)

C

- Examination of geoenvironmental conditions in the field
- Verification of forms in the field - research
  - * location
  - * surroundings
  - * morphology and morphometry

D

- Research to find traces of explosions on walls and at the bottom of craters
  - * geophysical
  - * geochemical

E

- Mapping and describing the conditions in which craters occur for the purposes of deep geophysical scanning
- Field-work planning
  - * areas of study
  - * selection of the profiles lines

F

- Conducting deep geophysical scanning down to different depths
  - * conductometric
  - * georadar

G

- Drawing up final results, preparing graphic and text materials
- Preparing instructions for spatial development

Fig. 9 Proposed action plan for UXB research. The range of activities performed as part of the research presented in this article has been marked in green (Prepared by J. M. Waga)

Conclusions

The bombed areas whose landform has not changed since WW2 provide greater opportunities for identifying potential UXBs than reclaimed and partly remodeled land. The application of high-resolution shaded relief rasters obtained from DEMs is an appropriate tool to accomplish this goal. Small craters with UXBs are frequently invisible, even in aerial photos from the 1940s. However, a large density of craters in areas affected by extensive bombardment impedes statistical analyses of particular drops and attempts to determine the existence of UXBs. The high density of bomb explosion sites resulted in the obliteration of the image of some minor UXB-derived craters.

Waterlogged and swampy areas are the most difficult places to conduct research that classifies the features of hollows. UXB fall sites are also unclear if bombs hit the bottoms of older craters filled with liquefied sediment and water. Due to the phenomenon of horizontal drift of UXBs in the ground, field geophysical verification of objects indicating, even to a small degree, a connection with UXBs is necessary.

Both individual UXBs and their clusters in areas of bombardment should be regarded as artifacts that co-create, along with the landscape of explosion craters, the remains of machinery and armaments, and the remains of military buildings, complexes documenting past armed conflicts. However, they involve real or potential risks to the public, including those conducting invasive research. For cognitive and practical (mainly safety) reasons, UXBs should be identified and located, and then, if warranted, excavated and neutralized. Archaeological research with modern methods, including remote sensing and geophysics, can help solve this problem.

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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