A Copper Alloy Light Cannon From Grodno – An Example of Early Firearms From Eastern Europe

Grzegorz Żabiński (g.zabinski@gmail.com)
Uniwersytet Humanistyczno-Przyrodniczy im Jana Dlugosza w Czestochowie https://orcid.org/0000-0003-3091-1035
Piotr Strzyż
University of Lodz Faculty of Philosophy and History: Uniwersytet Lodzki Wydzial Filozoficzno Historyczny
Tomasz Goryczka
Uniwersytet Slaski w Katowicach Wydzialu Informatyki i Nauki o Materialach
Krzysztof Aniołek
Uniwersytet Śląski w Katowicach Wydziału Informatyki i Nauki o Materiałach: Uniwersytet Slaski w Katowicach Wydzialu Informatyki i Nauki o Materialach
Ewelina Miśta-Jakubowska
National Centre for Nuclear Research Świerk

Research Article

Keywords: archaeometallurgy, copper alloys, Middle Ages, firearms, Grodno, Eastern Europe

Posted Date: March 8th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-267813/v1

Version of Record: A version of this preprint was published on June 5th, 2021. See the published version at https://doi.org/10.1186/s40494-021-00534-z.

Abstract

The paper discusses a recent find of a copper alloy light cannon discovered at the Old Castle in Grodno, Belarus. First, the archaeological and historical contexts of the discovery are dealt with. Then, the morphology and typochronology of the cannon are discussed and relevant analogies are proposed. Next, the technology of manufacture of the cannon is dealt with on the basis of metallographic examinations and EDS analyses of the metal's elemental composition. It was found out that the artefact had been made of leaded copper. The cannon can be dated to the late 14th c., as implied both by the find context, the morphology and the chemical composition of the artefact. Its deposition can possibly related to fights over the Old Castle in Grodno in this period, waged by Teutonic, Polish and Lithuanian forces. It can tentatively be assumed that the cannon was manufactured in a Teutonic Order's workshop, but further research is necessary to verify this supposition.

Introduction

The aim of this paper is to discuss a recent find of a late medieval light field cannon that was discovered in the course of excavations at the Old Castle in Grodno, Belarus. Although a great deal is known on late medieval firearms and early modern period, also concerning Central and Eastern Europe [1-4], the state of research on their manufacturing technologies is still unsatisfactory. Studies usually concern artefacts from single archaeological sites (e.g.,[5-6]), certain kinds of firearms [7-8], technology of firearms in a given country [9], or individual artefacts (e.g.,[10-11]). Sometimes results of technological examinations are integrated within regional studies on early gunpowder weapons (e.g.,[2]). Therefore, each technological study of medieval or early modern period firearms can be a chance to significantly broaden our knowledge in this field. In this case, the authors of this paper were offered an opportunity to carry out technological examinations of this newly discovered gun from Grodno. Apart from metallurgical analyses, the gun was dealt with in a broad historical and archaeological context. Furthermore, it was discussed against the background of development of late medieval and early modern period firearms, also with regard to questions of manufacturing technology.

Archaeological and historical contexts

Architectural and archaeological examinations were carried out in 2014 and 2015 at the Old Castle in Grodno. They were aimed at preparing ground for restoration works (on the castle itself see [12-15]). 14 trenches were opened altogether. Trench 13 was marked out in the lookout terrace in the courtyard along a defensive wall (Fig. 1), in a location where in 18th c. plans there was a remarkable curve in the wall (for the 18th plans of the castle see [12]). The defensive wall next to Trench 13 was constructed on top of a medieval defensive rampart at the end of the 14th or in the early 15th c. after strong fires from the 1390s (on this phase of the stronghold see [13]). In the 1580s, the defensive wall was repaired and in the 1930s it underwent conservation works. Buildings were constructed in this area in the 16th-18th c. [12; 13]. Due to this, the upper layers in Trench 13 were to a great degree mixed. The trench was trapezoid and its dimensions were 6.5 x 4 m. Cultural Layers 1 and 2 (sand padding under the pavement) in this trench were formed in result of land management works after excavations in the 1980s [13]. Both Layers 3 and 4 contained brown soil with brick rubble, fragments of roofing tiles, small vessel shards from the 16th-18th c., only Layer 3 showing presence of numerous pieces of 20th c. garbage. Layer 5 contained sandy clay, with numerous fired clay lumps. Cannon remains were found at Layer 5, adjacent to a 70x40-45 cm charcoal deposit showing thickness varying from 3 to 7 cm and located at a distance of approximately 14 cm from the northern side of the wall (Fig. 2). Numerous remains of melted copper were found adjacent to the cannon remains. A c. 40 cm thick layer of brown soil with traces of fire was found beneath the charcoal deposit. Pottery finds that were discovered there were dated to the second half of the 14th c. Beneath this layer there were cultural strata that were related to the construction of a defensive rampart in the 12th-13th c. (on this early phase of the stronghold see [13]; all data concerning the find context was kindly provided by Natalya A. Kiziukevič, Grodno State Historical and Archaeological Museum, personal communication, 20 April 2020).

In the period between the last quarter of the 14th and the early 15th c. Grodno and its vicinity became an area of intensive military operations. These were a result of political contacts between Grand Duchy of Lithuania and the Teutonic Order, with special stress on complex relationships between the Lithuanian Duke Jogaila (since 1386 Władysław II Jagiełło King of Poland) and his cousin Duke Vytautas. In Summer 1378, the Order launched an expedition against Lithuania and devastated the region of Podlachia with the strongholds of Brest and Grodno [16 p593, 597; 17 p107; 18 p48]. In 1384, Vytautas abandoned the Order's side and received in return the strongholds of Grodno, Brest, Drohiczyn, Mielnik as well as other territories [18 p89-93].

However, in 1389 Vytautas rose against Władysław and attacked Vilnius. After failing, he allied again with the Order in 1390 and gave it the region of Samogitia [18 p128-133]. In January 1390, the Order launched another military expedition to Lithuania and seized several strongholds, including Grodno and Brest. Władysław soon prepared a counterattack, and on 16 April 1390, Grodno was taken by Polish-Lithuanian troops. Interestingly, both Polish and Teutonic sources mention the use of firearms by the besieging forces [16 p640-641; 17

p162-163; 19 p162-163; 20 p180-182; see also 18 p134]. On this occasion it must be emphasised that for this period the use of firearms in this part of Europe was not limited to Teutonic or Polish troops. The Teutonic chronicler Wigand von Marburg frequently mentions cases of application of the new weapons by the Lithuanians as well [16 p613, 622, 633].

In November 1391, a new Teutonic expedition was led by the new Grand Master Konrad von Wallenrode as an ally of Duke Vytautas. In early December, the castle of Grodno was taken again by the Order's forces and was ceded to Vytautas. Wigand von Marburg said that firearms had been used by both parties (*fiunt varii conflictus bombardarum, sagittationes diverse*) [16 p646-647; 19 p174-176; see also 18 p137-138 and 21 p166].

In 1392, it came to another reconciliation between Vytautas and Władysław. In October, the Order invaded Vytautas' lands and in early January 1393 Grodno was taken and razed to the ground. Wigand von Marburg mentioned again an extensive use of artillery by the besiegers (*impugnant cum lapidibus bombardarum castrum*) [16 p649; 17 p185; 19 p185; 22 p623; see also 18 p172 and 21 p166]. The surroundings of Grodno became a basis of new Teutonic expeditions in early 1394 [16 p650-652; 19 p191; 22 p627; see also 18 p173].

On 23 April 1398, a treaty was made between the Order and Vytautas. According to it, the region of Samogitia became part of the Order's possessions [18 p179-181]. However, after another reconciliation between Vytautas and Władysław, in Spring 1401 it came to an anti-Teutonic uprising in Samogitia. The Order responded with military actions and in February 1402 Grand Marshall Werner von Tettingen ravaged the vicinity of Grodno [19 p256, 264-265; see also 18 p253-255].

On the basis of the archaeological stratigraphy and the historical evidence, it can be assumed with reasonable certainty that the cannon found in Layer 5 may have been in use during the Polish-Lithuanian-Teutonic conflicts in the last quarter of the 14th c. However, it seems much more complex to decide to which side of the hostilities it may have belonged.

Description and classification of the artefact

The artefact in its present shape was strongly affected by fire (Fig. 3A). The find consists of a main body and three detached fragments which must have originally belonged to the chase. The main body is a single cylinder that includes the breech part and the chase part, the latter being only partially preserved. Thus, the original shape of the cannon cannot be fully reconstructed. In the back part of the breech there is a primitive touch-hole, with no traces of a priming pan. A convex cross decorates one of the surviving metal fragments. This fragment perhaps comes from the muzzle and the cross may have served as a primitive aiming device (Fig. 3B). No lifting handle survived and no traces of it can be seen on the cannon's surface. A speculative reconstruction of the gun and its cross-section (as it can be proposed on the basis of similar surviving guns that are discussed below) can be seen in Fig. 4. The metrical data of the artefact are the following:

- total weight (surviving): 13.85 kg

- total length (surviving): 287 mm

- length of the chase (surviving): 84 mm

- length of the breech: 203 mm

- internal length of the powder chamber: c. 120 mm

- diameter of the powder chamber: c. 68 mm

- length of the bore (surviving): 206 mm

- external diameter at the breech: 122 mm

- external diameter at the muzzle (surviving): 221 mm

- internal diameter at the muzzle (calibre): c. 155 mm

- distance between the touch hole and the breech base: 82 mm

- diameter of the touch hole: 11 mm

- estimated weight of the projectile: c. 5260 g (granite)

- putative weight of the gunpowder's charge: c. 260 g (c. 1:20 proportion between the charge and the projectile, see [23 p14 or 24 p163]) or c. 400 g (assuming a 1:13 proportion, as proposed in [25 p28])

On the basis of its calibre it can be assumed that stone projectiles were used for the gun, which thus could be termed a *Steynbüchse* [21 p157; 23 p12; 24 p144]). A gun of such a size can be classified as a light field cannon. Such cannons could be either transported on carts and then placed on wooden stands or could be mounted on wheeled carriages [2 p84-92; 21 p159-160; 24 p60-61]. Schmidtchen states that in the case of early stone ball cannons a usual length proportion between the calibre and the powder chamber was c. 1:2 [23 p14]. In this case, it is merely 1: 1.3, which may support an assumption of an early chronology of the Grodno cannon. A relative narrowness of the powder chamber (c. 68 mm in this case) in relation to the calibre (c. 155 mm) is also considered a feature of early cannons of such type. This was aimed at securing a proper concentration of the explosion's impact and thus a better compression of the gunpowder charge [23 p14]. The archaeological context clearly implies a late 14th c. chronology of the cannon and this also receives support from analogous artefacts which are dealt with below. Nevertheless, it should be borne in mind that such cannons may have remained in use for much longer, as discussed later on in this paper.

Early firearms in Rus

Not much is known on the early history of firearms in Rus. The first mentions in written sources come from the late 14th c. It was recorded that defenders of Moscow used firearms against the Mongol siege in 1382. What was mentioned were "tyufyaki" (*тюфяки*) and large guns (*великiи пушки*) [26 p44], or simply guns (*поушки*) in another version of the report [27 p331-332; 28 p74]. The term "tyufyak" probably refers to lighter guns, which is also implied by the context. Another interesting record comes from 1389 and says that "in this year guns were brought from Germany" (*ТогожелѣтаизъНѣмецьбынесошапушкы*) [29 p444]. In 1394, guns (*пущичи*) were mentioned during the siege of Pskov by Novgorod Veliky's forces [30 p194]. In 1408, the Mongol Khan Edigey demanded Prince Ivan Mikhailovič of Tver to support him against Moscow with "guns and tyufyaki" (*съпушками, исътюфяки*) [26 p83; 31 p220-222; 32 p77-78]. McLachlan supposes that "tyufyaki" were large handgonnes and mentions 17th c. examples with calibres between 40 and even 85 mm [3 p41; see also 32 p85-87]. Wilinbachow assumes that the very term is of Eastern origin (cf. Persian *tufang*/*tupang* meaning "pipe" or "tube", or Turkish *tufenk*, which may have stood for early flamethrowers). He rejects an assumption that "tyufyaki" were cannons which were only used for firing shots. Instead, he proposes that full-sized projectiles were also used for such guns, which is also supported by later 17th c. records mentioning large stone, lead and iron ammunition. Interestingly, these records mention "tyufyaki" that were manufactured both of iron and from copper. According to Wilinbachow, "tyufyaki" were short-barrelled cannons analogous to early Western European bombards and they could mounted on wheeled carriages [33 p226-230, 232; see also 34 p28]. Wilinbachow also maintains that the appearance of early firearms in Rus was due to Western European and not Eastern (chiefly Mongol) influence [33 p218-220]. On the other hand, as in Kirpičnikov's opinion the earliest terms referring to firearms in Rus were of general Slavic ("puška"; this in fact comes from German "Büchse" and Latin "pixis" – G. Żabiński) and of Near East origin ("tyufyak") respectively, this researcher supposes that the new weapon reached the Rus lands from two directions, that is, from the West and the East. According to this scholar, the Western direction was more significant [32 p78-79]. In 1426, Lithuanian troops of Grand Duke Vytautas used guns (*пушки*) during an expedition against Pskov [35 p25; see also 32 p79]. An interesting mention is known from 1427 concerning an expedition of Vytautas against Novgorod Veliky. It says that Lithuanian troops took "guns, tyufyaki and handgonnes" (*пушки, и тюфяки, и пищали*). One of the guns, called "Galka" was so heavy that it was pulled by a team of 40 horses [26 p94; for a similar set of firearms mentioned in 1450 see ibid. p122-123; see also 24 p214-215 and 33 p227]. In 1444, guns (*пушки*) were used by both sides during the Teutonic siege of the fortress of Yam (Kingisepp) defended by Novgorod forces [36 p185; see also 31 p222]. In 1447, guns (*пушки*) sent by Duke Boris Alexandrovič of Tver were used during the siege of Uglič by Grand Duke Vasily II of Muscovy. In the same year, Duke Boris successfully applied guns in the siege of Ržev [29 p493; 31 p221-221]. Furthermore, from 1447 there comes a mention of the use of guns by the Novgorodians in a naval battle [36 p185; for similar events from 1459 see 30 p218; 31 p222]. A 1667-1671 description of firearms in Smolensk mentions a "copper *piščal* on a wheeled carriage, cast in Russia, whose length was 2 *aršins* and 2.5 *veršoks*" (c. 153 cm) (*Пищаль медная, в станку на колесах, Русского литья, длина два аршина полтрети вершка*). It was provided with a Russian inscription, saying that it was cast in 1483 by a master Yakov. Its weight was 16 *puds*, or c. 262 kg [37 No. 51, p304; see also 31 p225-226; 32 p81; 33 p232]. This record is coherent with an opinion that gun foundries came into existence in Rus in the late 15th c. [3 p41; 31 p223 ff; 32 p80-81].

Archaeological finds of early firearms from this part of Europe are not very numerous. One of the earliest artefacts is an iron-forged *mortira* found near Stary Krym in Crimea in 1885 (Fig. 5.1). This gun is dated to c. 1375-1425 and may be of Italian provenance, due to a strong presence of the Genovese in the peninsula. This gun is 44 cm long, its calibre is 8.1 cm and its weight is believed to be merely 11.5 kg. Another similar artefact of the same chronology is known from Ržev in Russia (Fig. 5.2). This gun is iron-forged, its total length is 46 cm and the calibre is 12.2-12.7 cm [34 p28, Fig. 4; 38 p59-60, Fig. 1; 39 p32, 34, cat. No. 1, Pl. 1]. As it can be seen, these guns are quite similar to the Grodno cannon, although they are iron and not copper alloy. A very interesting gun was discovered in the vicinity of Stary Krym in Crimea in 1966 and is now stored in the Museum of Antiquities in Feodosia (Fig. 6). Its total length is 895 mm and its calibre is 148 mm. This cannon is made of bronze and it is supposed that it may be of mid-15th c. Genovese origin. On the other hand, its Turkish (or local?) provenance cannot be excluded, either. The chase of the cannon is decorated with what seems to be an "Eastern" ornament (inscription?) [34 p27-28, Figs.1-2; 38 p60-62, Figs. 3-5]. Furthermore, a possibly mid-15th c. veuglaire was found in 1911 in the River Narva (it is stored now in the Military-Historical Museum of Artillery, Engineers and Signal Corps in St. Petersburg, inv. No. 1/1) [31 p222-223, Fig. 1].

An early handgonne dated to c. 1375-1450 was found somewhere in Central Russia and is now stored in the Ivanovo State Museum of History and Local Lore. A similar gun, dated to c. 1400 and possibly related to Rus-Mongol conflicts in the 1420s-1440s, was discovered in the River Lukh in the Vladimir Region [32 p87-88, Fig. 41, Pl. 28; see also 40 p42, Figs. 28 and 33]. Two fragments of hand-held gun barrels and an iron fitting of such firearms that may be dated to the late 15th-16th c. were found in the fortresses of Staraya Ladoga and Orešek in North-Western Russia [41 p220-224, Figs. 2.1-3].

Other analogies

One of the most obvious analogies is an early 15th c. light field Teutonic cannon from Kurzętnik (Kauernick) in Western Prussia (now North-Eastern Poland) (Fig. 7). This gun shares the same construction design with the cannon from Grodno, that is, a narrower breech and a wider chase. Its dimensions are the following: total length 507 mm, calibre 135 mm, length proportion between the calibre and the powder chamber 1:1.7, weight 42.28 kg. Technological examinations have demonstrated that this cannon was cast using copper with antimony (Sb) and lead (Pb) impurities. Regrettably, no quantitative analysis of the elemental content was carried out [21 p155-162, Figs. 1-9, p182, Fig. 37, p184-186, Fig. 38].

Attention is also drawn to a late 14th-early 15th copper alloy cannon of possibly Bosnian origin, now in the collection of the Museum für Deutsche Geschichte in Berlin (inv. No. W 347). Its total length is 65 cm, its calibre is 14 cm, its powder chamber diameter is 5.2 cm and the weight is 80.3 kg. The chase is somewhat wider than the breech, although this difference is not that pronounced as in the case of the cannon from Grodno [2 p87; 42 p36].

A convenient analogy is also offered by a light field cannon from the collection of the Zeughaus in Berlin. This gun is dated to the 2nd half of the 15th c. and is probably related to Burgundian-Swiss conflicts from the 3rd quarter of this century. It is made from iron bars and is provided with a holder and an additional iron ring. The barrel is 80.5 cm long, its calibre is 18.0 cm while the powder chamber's diameter is 5.0 cm. This gun is mounted on a two-wheel carriage, provided with an "aiming bracket" or a split-trail elevation [4 p310-311, No. 25].

An interesting artefact is stored in the collection of the Museum in Nový Bydžov in the Czech Republic (barrel length 53.5 cm, calibre 11 cm, powder chamber diameter 7.0 cm). The chase of this iron-forged field cannon is also wider than the breech, although the difference is not as prominent as in the case of the gun from Grodno. The chronology of the gun from the Museum in Nový Bydžov is estimated at the 1st quarter of the 15th c. [2 p85, 88-89, 366, Pl. 86, cat. No. 71; 42 p36; for other similar cannons see 2 p89; 43 p91-92, Figs. 2-3; 44 p182-187; 45 p165-176].

Another artefact which can be compared to the Grodno gun is a copper alloy field cannon from the fortress of Belgrade in Serbia. Its total length is 84 cm, the breech length is 40 cm and the calibre is 13 cm. The chase is somewhat wider than the breech. This gun can possibly be dated to the 1st half of the 15th c. and its deposition may be related to the Turkish sieges of Belgrade in 1440 or in 1456 [2 p87-88, Fig. 11; 46 p20; 47 p135, Fig. 71].

Similar guns are often depicted in late medieval and early modern period manuscripts. A good example of a light cannon on a wheeled carriage provided with an "aiming bracket" can be seen in the *Anleitung, Schiesspulver zu bereiten Büchsen zu laden und zu beschiessen*. from the early 15th c. (Fig. 8.1). A similar example is displayed in *Das Buch von der Büchsenmeisterei*, dated to the 1460s (Fig. 8.2). The same manuscript features yet another gun of this kind, but in this case it is mounted on a much more complex wheeled carriage, which seems to enable the cannon to be moved both in the vertical and the horizontal plan (Fig. 8.3). Analogous light cannons on wheeled carriages with "aiming brackets" can also be seen in the München copy of Maximilian I's *Zeugbuch* from the beginning of the 16th c. (Figs. 10.4-5).

Technology of early copper alloy firearms

Barrels of early firearms in Europe were made of two basic raw materials – iron and steel [1, p13-19; 2 p105-106, 232-238; 10; 11; 43 p90], as well as from copper and its alloys [1 p11-13; 2 p214-232; 43 p90; 51 p33-34]. As regards manufacturing of copper alloy firearms, in the case of smaller cannon barrels the lost-wax or *cire-perdue* technique may have been applied. In this approach, the core was first prepared using a wooden shaft which was wrapped with ropes and was then covered with clay. The surface of the core was then covered with tallow and wax. In a variant of this technique, the entire core (which played the role of a so-called "false" or "counterfeit model") could be prepared from wax. In the next stage, a clay mould was formed around the core. The mould was then fired and the wax was thus removed by melting it away through openings in the mould [2 p225-226; 9 p95]. Concerning barrels of hand-held firearms, in the end of the first half of the 15th c. a new technology on the basis of wooden models was introduced, which allowed for the serial production of barrels. Such models were then covered with clay to form the mould which was then reinforced with iron rims. After the mould had been dried, the model was removed and it was replaced with an iron core [2 p225-227].

The process of casting a large Turkish cannon's breech during the siege of Constantinople in 1453 was described by Kritoboulos in 1467. First, the cylindrical core was prepared with the use of clay and linen. Then, a clay and linen mould was made and it was additionally strengthened using timber, wood, stones and earth. The core was placed inside the mould in such a manner that empty space for the cast metal was left (Kritoboulos' account after [52 p186-187]).

The process of cannon barrel casting was discussed in a very detailed manner by a Sienese metallurgist Vannoccio Biringuccio in the first half of the 16th c. First, a pattern exactly reproducing the shape of the gun is prepared. This pattern is usually made on a wooden beam pivoted on trestles. The beam may be wrapped around with a rope and is covered with clay and ash. Then, a ball-shaped feeding head is prepared, which will be placed at the mouth of the gun. Next, two clay or wooden discs are made. These will be placed at both ends of the model. They will serve as sockets which will accommodate both ends of an iron core. After the trunnions are made and are fastened with nails to the pattern, they are covered with layers of ash and tallow. The next step is a preparation of the mould which is made of layers of loam, additionally reinforced with a "cage" of iron rods and bars, covered with another layer of clay. The mould is dried and heated and when the wax and tallow between the pattern and the mould are melted, the pattern is removed. A so-called collar (an iron ring with four "legs" placed crosswise) is then placed at the end of the mould in order to hold the core in the centre of the mould. The aforementioned core is made from an iron spindle covered with ash, ropes, hemp tow and a mixture of various components. Layers of clay and dung are put on until the core's thickness roughly matches the projectile's diameter. In the next step, the breech's mould is prepared analogously to the barrel's mould [53 p234-246]. Having discussed some other technical details [53 p246-249], Biringuccio deals with the casting process itself. The mould (see Fig. 9) is vertically placed in a pit in front of the furnace and the core is fixed in the middle of the mould [53 p249-260]. Some data on the alloy composition is given in an earlier chapter of Biringuccio's book. For bronze, a usual proportion is 8-12 pounds of tin per 100 pounds of copper (i.e., 7.4-10.7% Sn and 89.3-92.6% Cu) while the best recipe for bells is 23-26 pounds of tin (i.e., 18.7-20.6% Sn and 79.4-81.3% Cu). For "all other works" the content of tin is 12 pounds (i.e., 10.7% Sn) or more [53 p210-211]. In the course of casting attention must be paid to the melting loss of material, which is usually c. 5-8%, but it may be even 10% [53 p266]. Furthermore, Biringuccio recommends to add some tin at the end of the process to make sure that the alloy will be of proper ductility and will be devoid of holes [53 p259-260]. Eventually, the gun is extracted from the pit, the clay mould and the core are removed and finishing work is carried on [53 p307-312].

Numerous fragments of clay and metal moulds for casting cannons, many loose lumps of clay and copper alloy, as well as remains of casting installations were discovered in the Teutonic Order's capital Castle of Marienburg (Malbork) at the site of a former foundry. The maximum calibre of cannons that were cast there was assessed at c. 33-43 cm [54 p21-29, Figs. 4-6, 11; 55 p303-305, 308-311, Figs. 5-8]. Furthermore, written records from the Teutonic Order's state in Prussia contain numerous references to gun casting [9 p99-101]. Remains of a gun foundry from the late 15th-early 16th c. were also recorded in the course of excavations at the castle hill in Buda in Hungary [56 p156, 158-165, Figs. 4-10, 12-14].

In Central Europe, numerous examples of the earliest primitive handgonnes and hackbuts from the late 14th-early 15th c. were made of copper alloys [2 p30-34, 36-37]. Copper alloy handgonnes were also in use in the 2nd-3rd quarter of the 15th c. [2 p39-41]. Interestingly, in this period there seemed to be (at least locally) a preponderance of copper and copper alloy hackbuts over iron ones [2 p47-51; 24 p100; see also 57 p113-121]. Copper alloy barrels can also be found in hand-held firearms in the 2nd half of the 15th-early 16th c. [2 p55-56, 63-64]. A preponderance of copper hand-held firearms in the first half of the 15th c. has also been suggested for other places in Europe (Frankfurt am Main or Hildesheim, see [58 p68-71, 301-304]). Perhaps this was not a universal rule. Iron hand-held firearms may have prevailed in Köln around the mid-15th c. [58 pp. 316, 454], and there may have been a sort of equilibrium between iron and copper alloy guns in Burgundy in this period [4 p217; 58 p555-556]. Interestingly, late 14th-15th c. hand-held firearms barrels from Rus were made of iron [40 p24-25, 36, 38-39].

Among the surviving specimens of one type of early light artillery in Central Europe (so-called terrace-guns) there is an almost total absence of copper alloy barrels and nearly all preserved artefacts were iron. On the other hand, written sources from the first half of the 15th c. mention copper or bronze barrels of such cannons much more frequently than iron ones [2 p78, 80-81]. Concerning light field cannons, to which the Grodno gun belongs, both iron and copper or copper alloy artefacts are known. Furthermore, copper guns are known from written sources [2 p85-92]. Among veuglaires there is a preponderance of iron barrels, although copper and copper alloy ones are mentioned by written records, too [2 p93-101]. Concerning bombards (or the largest cannons), iron and a stave-and-hoop construction were preferred in Europe [1 p20; 2 p104-106, 108-109, 232-233; 4 p204-262-267; 7; 8; 24 p. 63, 76, Tab. 2, 80-82; 42 p79-80, Tab. 1]. On the other hand, huge bronze cannons are known both from surviving artefacts and from written sources [1 p20; 2 p104-106, 108-109, 232-233; 24 p76, Tab. 2, p82; 42 p81, Tab. 2; 52]. In general, it can be assumed that in the period to the mid-15th c. copper alloy guns were more popular than iron ones [2 p213-214]. An interesting proportion between copper and iron cannons was mentioned with regard to the siege of Saint-Saveur-le-Vicomte by the army of King Charles V of France in 1375. The royal army had as many as 24 copper bombards and merely 5 iron ones [59 p156]. Copper cannons were dominant in Dijon in Burgundy in the second half of the 14th c. [58 p555-556]. However, most veuglaires in Burgundy in the period from 1417 to 1467 were made of iron [4 p234]. As regards the Italian Peninsula in the late 15th-early 16th c., iron cannons were still in use, but the significance of bronze ordnances, especially the largest ones, was constantly increasing [60 p756-770, Tab. 1]. Copper cannons in castles and towns in the south-eastern part of the Habsburg realm (present-day Slovenia) are sometimes mentioned in the afore-mentioned München copy of Maximilian's *Zeugbuch* from the early 16th c. [44 p96-99; 61 p66-67; 62].

The Teutonic Order was one of the parties involved in fights over Old Castle in Grodno. Therefore, it is worth paying attention to abundant data in written sources concerning the technology of manufacture of copper alloy firearms in the Teutonic Order's state in Prussia. Regrettably, nothing comparable is available for Poland (where firearms are first mentioned in 1383 [2 p33; 24 p14, 230; 42 p16]) or Lithuania. For the Order's state, the first mention on the use of firearms in narrative sources comes from 1362, while the earliest inventory record is known from 1374 (21 p165; 23 p24, 26; 24 p12]. Mentions of copper guns in the Order's accounts and inventories sources are not frequent. On the other hand, it is evident that a difference between copper and bronze guns was known to the authors of these records, as they make a distinction between *kopperyne/kopperen* (copper) and *erynne/eren* (bronze) firearms [9 p86-88]. Copper firearms in the Teutonic Order's state were either hand-held guns or lighter cannons [9 p86; 21 p173, 178, 180].

Concerning a general pattern of use of raw materials (copper and its alloys versus iron) for gun barrels in the Teutonic Order's state in the period between the late 14th and the early 16th c., there was a preponderance of copper and copper alloy guns over iron ones. 385 guns were recorded in written sources, and more than 65% of these were made using copper and its alloys, copper guns being more than 17% [9 p84-88, Tab. 1]. This may validate the afore-mentioned observation concerning the dominance of copper alloys in some regions of Europe in the early period of firearms development.

A preponderance of copper alloys is even more visible in manufacture and purchase of new firearms, although it must be remembered that the lion's share of this data comes from a narrow period of the early 15th c. In this case, among 103 acquired guns, almost 80% were made using copper and its alloys, the share of copper guns being about 6.8%. A dominance of copper alloys is even more pronounced in the case of artillery (92.7% cases) and almost all the largest guns acquired by the Order were made of bronze. It has been suggested that bronze was considered the best material for the heaviest cannons by the Order, in spite of the fact that bronze was more expensive than iron. This could imply that more attention was paid by the Order's authorities to quality issues than to economic aspects of firearms acquisition ([9 p87-92, Fig. 2; on quality issues of bronze and iron artillery see also, e.g., [60 p756-757]).

According to written sources, the Teutonic Order's guns cast at Marienburg (Malbork) in 1401 were manufactured of almost pure copper (about 97-97.5% Cu). A rather low amount of tin (about 2.5-3% Sn) did not have much influence on its utilitarian properties. Provided that these guns were of more or less equal weight, it can be supposed that they were rather small ordnances (about 120 kg each). Therefore, their manufacturers may have assumed that such a composition would suffice to provide these guns with proper toughness. Concerning two veuglaires from 1403, the proportion of tin was much higher (almost 11% Sn). These ordnances may have been smaller than the guns from 1401 and the total weight of one cannon with three powder chambers was perhaps a bit more than 100 kg, that is, perhaps about 70-76 kg for the chase with one chamber. In this case, it could be tentatively assumed that these veuglaires were manufactured using tougher and harder metal as they were exposed to stronger wear in result of a higher rate of fire [9 p101-103; 24 p107; 25 p22].

In the case of the three largest Teutonic cannons the chemical composition varies. Regarding the largest ordnance, that is, the *Grose Bochse*, the content of tin is nearly 13% Sn, which may suggest extra toughness. The amount of tin was even higher (nearly 17.5% Sn) in the case of the *Bochse nest der grosen*. On the other hand, worth noting is the share of lead (0.85% Pb) in the metal of the *Grose Bochse*. It was added on a single occasion only, when the chase of the ordnance was cast again. As regards the *Lange Bochse* from 1409, its tin content (more than 5.5% Sn) is more similar to that in the smaller cannons than in the largest ordnances [9 p103; 23 p56, 58-60; 51 p32-33, Tab. 1].

Technological examinations of the cannon from Grodno

Methods

Four samples were analysed altogether – three of these (Samples 1-3) came from the loose parts of the chase found with the cannon, while Sample 4 was taken from the front edge of the chase part within the gun's main body. The samples were mounted in Electro-Mix electroconductive resin, ground on SiC papers (500-2000 grits) and polished with diamond pastes (6, 1 and 0.5 μm). Next, they were etched with a Mi17Cu reagent (10g $FeCl_3$, 30ml HCl, 120 ml C_2H_5OH) for 2 seconds in order to reveal the microstructure. Metallographic observations (for Samples 1 and 4 only) were carried out with an OptaTech MM100 inverted metallographic microscope (magnifications x50-x200; bright field) coupled with a 16 mpx digital camera. Chemical composition analyses of all samples were carried out with a JEOL JSM-6480 scanning microscope operating at 20 kV and equipped with an EDS-type detector. The equipment was energy calibrated using an Al-Cu standard reference sample. The measurement time was 50 s per point and quantitative analyses were done using the non-pattern method. The detection limit was 0.1wt%, and the measurement error was <10% for major elements (above 1.0wt%) and <30% for minor elements (below 1.0wt%). Results are averages of several measurements over the whole surface of each sample (see Table 1). While discussing the results of the technological analyses it must be remembered that the artefact was found in a fire-related archaeological layer. Thus, a prolonged exposure to heat may have influenced the cannon's microstructure.

Results And Discussion

Microscopic observations have revealed the presence of high pore density in the metal of the cannon (an effect of gases remaining in the liquid in the course of solidification), especially in Sample 4 from the chase (Figs. 10b-c, 11a-b, 12ab, df, and 13a-b). The pores are regular in shape, which may indicate that they were formed while the liquid metal was poured into the mould and were trapped by crystallisation processes. This suggests that the metalworker was not competent enough to avoid the formation of undesirable structures in the metal, which could actually have an adverse effect on the mechanical properties of the material (cf. [52 p192-193]; on porosity in castings see also [63 p88]). Interestingly, considerable porosity of the microstructure was also found out in the case of the Teutonic light cannon from Kurzętnik (Kauernick) [21 p182, Fig. 37, p186]. The method of casting of the artefact also influenced the shape and size of grains. These are usually equiaxial and their sizes strongly vary. In most cases these are 100-200 μm in diameter, but larger grains of up to 500 μm were observed as well (Figs. 10b, d, f, 11a-b, 12b, d, f, and 13a-b). Usually, grains in archaeological alloys are smaller, values below 50 μm being the most frequent [63 p59, Fig. 3.38]. There are no grain elongations and the grain shape is usually regular, which indicates that the metal did not undergo any cold-working after casting (cf. [64 p42-44]). No dendritic structures which remain in as-cast metals [63 p58-59, 83] can be seen. Repeated annealing usually removes such structures [5 p93-94; 63 p100-101], but in this case, annealing may have taken place in result of the artefact's exposure to heat. This may have occurred both during a fire of the Old Castle in Grodno or in the course of combat use of the gun.

Inclusions were found in some places in the Cu alloy matrix (Figs. 10e, 11b, and 12c,e-f). The EDS examinations demonstrated that the inclusions in the metal gun mainly contained Cu, S, Pb, Sn and Fe (see Tab. 1 below). Thus, they may be copper sulphides, which are among the main corrosion products of copper. Sulphide inclusions (Cu_2S or others) can frequently be found in archaeological copper alloys [63 p89, Fig. 4.22, p92-94, Fig. 4.28; 65 p76, Fig. 5].

The EDS examinations demonstrated that the cannon from Grodno had been cast using leaded copper (Tab. 1). The average value of Cu is 90.96%, the Sn content is 1.01%, while the content of Pb is 3.77%. This implies that lead may have been deliberately added to improve the alloy's ductility (cf. [5 p94]; on leaded copper see also [63 p153-154]). The content of Sn is 1.00%, which is too low to have any practical influence on the alloy's properties. The amount of Sb (0.76%) may have somewhat increased the metal's toughness, but its low content suggests that Sb was impurity [63 p137, 139-143] and not intentional additive to the alloy.

Table 1. Elemental composition of the cannon from Grodno (wt%).

	Cu	Pb	Sn	Al	Si	S	Ti	Cr	Mn	Fe	Ni	Zn	As	Ag	Sb	Total
Sample 1 (Chase Part 1)																
Zone 2 inclusions																
Point 1	75.83	3.75	0.43	0.84	0.11	14.79	0.27	0.12	0.25	1.39	0.56	0.34	0.00	0.24	1.08	100.00
Point 2	79.90	3.73	0.78	0.56	0.00	12.30	0.19	0.36	0.16	0.29	0.40	0.29	0.00	0.52	0.52	100.00
Point 3	74.91	2.72	0.45	0.46	0.00	15.16	0.00	0.18	0.23	3.06	0.23	0.80	0.00	0.58	1.22	100.00
Zone 2 matrix																
Point 4	92.99	3.18	0.65	0.13	0.10	0.22	0.18	0.21	0.17	0.25	0.32	0.40	0.13	0.54	0.53	100.00
Zone 4 inclusion																
Point 5	73.34	4.86	0.40	0.84	0.00	17.35	0.21	0.40	0.10	0.58	0.56	0.29	0.30	0.00	0.78	100.00
Zone 4 matrix																
Point 6	91.14	3.99	1.62	0.12	0.27	0.00	0.25	0.19	0.10	0.27	0.42	0.30	0.00	0.82	0.50	100.00
Area 9.375 mm^2	90.40	5.30	0.73	0.00	0.40	0.00	0.33	0.20	0.23	0.18	0.40	0.36	0.00	0.84	0.62	100.00
Avg matrix	91.51	4.16	1.00	0.08	0.26	0.07	0.25	0.20	0.17	0.23	0.38	0.35	0.04	0.73	0.55	100.00
SD matrix	*1.33*	*1.07*	*0.53*	*0.07*	*0.15*	*0.13*	*0.07*	*0.01*	*0.06*	*0.05*	*0.05*	*0.05*	*0.08*	*0.17*	*0.06*	
Sample 2 (Chase Part 2)																
Matrix																
Point 1	91.57	4.71	0.33	0.15	0.29	0.10	0.25	0.22	0.26	0.21	0.27	0.49	0.00	0.44	0.71	100.00
Point 2	91.36	3.99	0.80	0.21	0.14	0.00	0.22	0.43	0.15	0.24	0.23	0.61	0.00	1.06	0.54	100.00
Point 3	92.16	3.55	1.05	0.34	0.00	0.00	0.15	0.19	0.18	0.26	0.00	0.43	0.00	0.33	1.37	100.00
Point 4	94.26	2.46	0.96	0.14	0.00	0.00	0.26	0.15	0.15	0.24	0.19	0.24	0.00	0.62	0.32	100.00
Point 5	90.13	5.19	0.49	0.00	0.24	0.00	0.30	0.37	0.13	0.26	0.18	0.72	0.00	1.04	0.94	100.00
Point 6	91.23	2.76	0.47	0.10	0.37	0.00	0.17	0.00	0.21	0.55	0.27	0.44	1.46	1.11	0.87	100.00
Point 7	92.07	3.75	0.55	0.13	0.23	0.00	0.15	0.15	0.11	0.31	0.17	0.47	0.21	0.69	1.01	100.00
Point 8	91.19	3.86	1.22	0.00	0.30	0.10	0.27	0.26	0.13	0.35	0.42	0.49	0.30	0.53	0.58	100.00
Point 9	90.22	5.20	1.12	0.14	0.14	0.17	0.14	0.15	0.10	0.27	0.33	0.53	0.00	0.60	0.89	100.00
Point 10	92.24	1.83	0.94	0.20	0.25	0.38	0.31	0.18	0.20	0.38	0.29	0.54	1.16	0.61	0.53	100.00
Avg matrix	91.64	3.73	0.79	0.14	0.20	0.07	0.22	0.21	0.16	0.31	0.23	0.50	0.31	0.70	0.78	100.00
SD	*1.17*	*1.13*	*0.31*	*0.10*	*0.12*	*0.12*	*0.06*	*0.12*	*0.05*	*0.10*	*0.11*	*0.13*	*0.54*	*0.27*	*0.30*	

matrix																
Sample 3 (Chase Part 3)																
Matrix																
Point 1	89.82	5.07	0.89	0.13	0.29	0.00	0.33	0.23	0.23	0.23	0.59	0.39	0.61	0.66	0.54	100.00
Point 2	91.20	2.91	1.05	0.13	0.36	0.00	0.28	0.26	0.21	0.37	0.65	0.98	0.00	0.72	0.87	100.00
Point 3	90.44	4.08	1.26	0.23	0.32	0.24	0.29	0.24	0.24	0.60	0.41	0.36	0.00	0.49	0.81	100.00
Point 4	90.62	3.58	1.14	0.10	0.26	0.00	0.23	0.29	0.37	0.45	0.37	0.66	0.13	0.70	1.10	100.00
Point 5	91.13	1.67	1.48	0.28	0.12	0.00	0.25	0.33	0.45	0.27	0.40	0.92	0.97	0.82	0.93	100.00
Point 6	89.75	3.88	1.12	0.00	0.26	0.15	0.30	0.31	0.20	0.38	0.73	0.66	0.44	0.78	1.04	100.00
Point 7	89.80	4.59	1.03	0.16	0.21	0.20	0.29	0.37	0.11	0.40	0.39	0.62	0.00	0.85	0.99	100.00
Point 8	90.57	0.87	1.43	0.10	0.21	0.00	0.38	0.59	0.20	0.44	0.77	1.18	1.69	1.14	0.44	100.00
Point 9	89.24	0.89	1.43	0.00	0.52	1.15	0.45	0.40	0.13	1.15	0.60	0.80	1.26	1.40	0.58	100.00
Point 10	88.92	5.45	0.78	0.00	0.19	0.00	0.37	0.37	0.32	0.40	0.74	0.31	0.29	0.67	1.20	100.00
Avg matrix	90.15	3.30	1.16	0.11	0.27	0.17	0.32	0.34	0.25	0.47	0.57	0.69	0.54	0.82	0.85	100.00
SD matrix	*0.77*	*1.67*	*0.24*	*0.10*	*0.11*	*0.35*	*0.07*	*0.11*	*0.11*	*0.26*	*0.16*	*0.29*	*0.59*	*0.26*	*0.26*	
Sample 4 (chase)																
Zone 1 matrix																
Point 1	89.40	5.27	0.95	0.00	0.40	0.00	0.46	0.15	0.41	0.31	0.68	0.70	0.00	0.41	0.86	100.00
Zone 1 inclusion																
Point 2	70.23	3.79	0.45	0.19	0.00	22.34	0.44	0.27	0.20	0.37	0.36	0.34	0.00	0.00	1.03	100.00
Point 3	69.16	2.78	0.75	0.40	0.00	23.36	0.38	0.18	0.19	0.35	0.60	0.32	1.05	0.00	0.49	100.00
Zone 2 inclusion																
Point 4	69.08	4.15	1.04	0.13	0.13	22.14	0.45	0.24	0.20	0.81	0.39	0.33	0.00	0.24	0.67	100.00
Zone 2 matrix																
Point 5	92.29	1.76	0.99	0.13	0.28	0.00	0.26	0.24	0.17	0.31	0.31	0.58	0.50	0.63	1.57	100.00
Zone 3 inclusion																
Point 6	70.29	4.67	0.40	0.19	0.00	21.30	0.25	0.37	0.17	0.27	0.41	0.33	0.14	0.40	0.81	100.00
Zone 3 matrix																
Point 7	92.54	2.26	0.83	0.00	0.10	0.13	0.47	0.35	0.19	0.31	0.31	0.26	0.26	1.10	0.88	100.00
Zone 4 matrix																

Point 8	90.53	4.67	1.49	0.00	0.10	0.18	0.19	0.13	0.00	0.29	0.45	0.41	0.15	0.44	0.99	100.00
Point 9	90.10	5.40	0.82	0.33	0.00	0.00	0.30	0.22	0.14	0.44	0.31	0.65	0.00	0.76	0.55	100.00
Point 10	91.62	3.02	1.19	0.00	0.13	0.00	0.37	0.16	0.00	0.34	0.60	0.70	0.24	0.91	0.73	100.00
Point 11	90.43	4.17	1.01	0.15	0.18	0.00	0.18	0.39	0.19	0.35	0.33	0.79	0.00	0.64	1.19	100.00
Point 12	90.49	3.26	1.30	0.11	0.21	0.15	0.50	0.34	0.19	0.41	0.69	0.34	0.34	1.05	0.63	100.00
Point 13	89.05	5.19	1.03	0.00	0.43	0.00	0.25	0.32	0.20	0.53	0.42	0.73	0.40	0.95	0.51	100.00
Avg matrix	90.72	3.89	1.07	0.08	0.20	0.05	0.33	0.25	0.16	0.37	0.46	0.57	0.21	0.76	0.88	100.00
SD matrix	*1.21*	*1.37*	*0.22*	*0.11*	*0.14*	*0.08*	*0.12*	*0.10*	*0.12*	*0.08*	*0.16*	*0.19*	*0.19*	*0.25*	*0.34*	
Avg all matrix	**91.00**	**3.77**	**1.01**	**0.10**	**0.23**	**0.09**	**0.28**	**0.25**	**0.18**	**0.34**	**0.41**	**0.53**	**0.28**	**0.76**	**0.76**	**100.00**

In order to trace possible technological similarities between the Grodno cannon and other guns, these results can be compared with observations concerning the elemental composition of other firearms. The number of medieval and modern period copper alloy firearms which underwent technological examinations focusing on their elemental composition is far from satisfactory. However, a short list of results was prepared on the basis of available literature (including data from late medieval written sources). Concerning written sources, for obvious reasons a prominent place is held by records related to the Teutonic Order. It must naturally be remembered that individual cases are not always fully comparable due to different analytical methods (in most cases, these guns were examined with the XRF method), equipment, research procedures (especially sampling strategies), and so on. Furthermore, late medieval written sources offer rather estimates than exact figures and these obviously contain data on a few major elements only. Nevertheless, some interesting hypotheses can be proposed (see Electronic Supplement, Sheet 1, all data in wt%).

The first important observation is that although later guns (i.e., those dated to the second half of the 15th c. or later) were usually made of raw material with less than c. 95% Cu, there are also artefacts whose alloy contains a higher amount of this element. Such firearms could perhaps be termed “copper guns” by people of those days. The use of alloy with c. 95% Cu or more seems to have been limited to hand-held firearms and lighter guns, a 9100 kg heavy Swiss cannon from 1409 being a notable exception. Regarding the heaviest cannons, most of these were cast using bronze containing at least c. 10% Sn, which seems to match toughness requirements that were expected in the case of such ordnances. Attention is also drawn to the share of Pb, which may even reach more than 15%. This may be a result of compositional differences between various parts of a given gun. In the case of some 16th c. cannons from a Venetian shipwreck found near Sv Pavao in Mjlet Island (Croatia), the amount of lead was the lowest in the muzzle and the highest in the breech. What is more, these differences may also be due to sampling procedures [6 p157]. Samples were taken from surface layers, and as the temperature of solidification of Pb is lower than that of Cu and Sn, Pb tends to migrate to the surface. Thus, the results obtained on the basis of samples taken near the surface are not representative for the chemical composition of entire artefacts [66 p57]. A similar observation concerning the varying amount of Sn in the alloy due to different solidification temperatures of Cu and Sn was stated by Morin for two 16th Venice cannons [67 p10]. It is of interest that a considerable amount of Pb can be found both in hand-held firearms as well as in cannons. Lead may have been added to secure better casting properties and elasticity [5 p94, 101-102; 68 p3063-3064], but the actual effect of a too high content of Pb on the gun’s performance may have in fact been the opposite [9 p103].

There are other guns where the contents of Cu (about 90%) and Sn (about 1-2%) are similar to those in the Grodno gun (Electronic Supplement, Sheet 1, Nos. 10-11, 32-33, 55-56), but the content of Pb was usually different (either below 1% or above 6%). Concerning guns where the Pb content was similar (i.e., about 3-5%) to that in the Grodno cannon, it was usually accompanied with a higher content of Sn (above 5%, sometimes even 8-9%) (Electronic Supplement, Sheet 1, Nos. 35, 47-50, 65), which certainly influenced the alloy’s properties. Only in the case of a 15th c. hand-held gun from Valečov in Bohemia the contents of Cu, Pb and Sn were close to those in the Grodno cannon (Electronic Supplement, Sheet 1, No. 11 – 93.03% Cu, 4.32% Pb and 1.04% Sn). Similarities were also found concerning the front sample from Cannon 3 from the 16th c. shipwreck in Sv Pavao, Croatia (Electronic Supplement, Sheet 1, No. 32 – 91.15% Cu, 4.27% Pb, and 1.21% Sn), but this is obviously not representative for the entire gun (Electronic Supplement, Sheet 1, Nos. 32-34 and their average chemistry).

In order to better visualise possible technological similarities, results were normalised to 100% and were displayed in on a Cu-Pb-Sn ternary graph (Fig. 14) (see also bivariate scatterplots of Cu-Sn, Cu-Pb, and Pb-Sn, Electronic Supplement, Sheets 3-4). Observations where variables were missing were discarded. For the sake of a greater representativeness, data from individual samples and not averages for the entire guns were used. All operations were carried out in XLSTAT, Ver. 2021.1.1. The aforementioned similarity between the Grodno cannon, the hand-held gun from Valečov and the front part of Cannon 3 from Sv Pavao is evident. With regard to a high amount of Cu and a low amount of Sn (3% or less), attention is also drawn to late 14th c. bolt gun from Loshult in Sweden, a mid-15th c. hand-held gun from Wenecja in Greater Poland, two mid-15th c. hand-held guns from Mstěnice in Moravia, and a 16th c. swivel gun from Benin in Nigeria. It is worth noting that all these are either hand-held firearms or light cannons. Therefore, in the case of the Grodno gun the amount of elements which were the most crucial from a utilitarian point of view is not uncommon for light firearms. The choice of alloy for the Grodno gun have been meant to facilitate the manufacturing process, as no extra toughness was needed in such a light field cannon.

Possible provenance of the Grodno gun

Provenance of an archaeological find understood as the place or region where it was made and provenance of its raw material are in many cases two different things. This is especially true for copper alloy artefacts, as copper ores are by far not that frequent as, e.g., iron ores. Regarding the place of manufacture of the Grodno gun, the archaeological and historical evidence could equally suggest a Teutonic or Polish workshop. Its Rus-Lithuanian manufacture seems much less probable, as all known early firearms from this part of Europe are iron. Its Teutonic provenance could only tentatively be supposed, based on an established tradition of manufacture of copper guns by the Order. It must be remembered, however that much more is known on the technology of manufacture of copper alloy firearms in the Teutonic Order's state than in Poland or the Grand Duchy of Lithuania in the discussed period [2 p214-232].

A few attempts at assessing the provenance of metal in copper alloy firearms have been undertaken in previous research. Concerning two late medieval hand-held guns from Kalisz and from Wenecja (both in Greater Poland), on the basis of the content of As (1.19% and 1.56% respectively) a Polish source of metal has been proposed, but with no further details [2 p229]. Regarding the late medieval hand-held guns from Rakov and from Valečov in Bohemia, it has been suggested that the contents of Ag and Sb (Rakov – 2.1% Ag and 2.4% Sb; Valečov – 0.26% Ag and 0.58% Sb) may imply that the metal came from Bohemian mines in Kutna Hora [2 p230]. As far as three copper alloy late 16th-early 17th c. Venetian cannons from the wreck site of Megadim in Israel are concerned, Ashkenazi et al. have stated that similarities in their chemistry may suggest the same raw material. Furthermore, they have suggested that Pb isotopic examinations may be of use to assess the metal's provenance. This, however, could be related to certain difficulties, as in two cannons the content of Pb was below 1 wt% [5 p101].

In the recent years there has been a considerable progress in copper provenance analyses using Pb isotopic ratios, often combined with minor elements (e.g., Sb, As, Ni, and others) (for a historical outline and a theoretical background see, e.g., [69 p27-35; 70 p239-263; 71 p13-14]). Hauptmann et al. discussed Late Chalcolithic and Early Bronze Age artefacts from Arslantepe in Anatolia [72]. Pb isotopic ratios were used by Niederschlag et al. for the purpose of defining the provenance of Early Bronze Age copper and bronze artefacts from Bohemia, Central Germany and Poland [73]. Prehistoric copper ore mining in the Eastern Alps has been a subject of several studies on the basis of Pb isotopic ratios and trace elements (Ag, Sb, Ni, As, and others) [74; 75; 76]. Pryce et al. have carried out a broad-scale study on South Eastern Asian copper alloy exchange in the period of c. 1000 BC-c. 500 AD [77]. Pollard and Bray paid attention to behaviour of certain elements (As, Sb, Ag, Ni) and in alloys during alloy re-melting and their significance in characterising the metal during its life history. Combined with observations on the contents of Sn, Zn, and Pb as major alloying elements, this allowed for a new look on patterns of copper alloy recycling. These scholars also proposed an new approach, where the Pb chemical concentration is used together with its isotopic ratios [78]. Rademakers et al. investigated copper provenance in Late Bronze Age Egypt [79], and the provenance of copper artefacts from the Early-Middle Copper Age in the Great Hungarian Plain was discussed by Siklósi and Szilágyi [80]. Nørgaard et al. discussed questions of provenance and circulation of copper alloys in Early Bronze Age Scandinavia [81]. There is also a recent provenance study by Kowalski et al. on the basis of Ag-Sb and Pb/As-Pb bivariate scatterplots [82]. The state of debate on the provenance and use of metals in Bronze Age Europe has recently been discussed by Radivojević et al. They reviewed a number of issues, including research and presentation standards, or a significance of open access online data repositories (OXALID and others). Attention was paid to methods of provenancing and their limitations, especially those caused by recycling and mixing of metal. Questions of copper distribution and circulation patterns were also dealt with [83].

However, on the basis of the available data it is impossible to propose a provenance of the metal of the light field cannon from Grodno. This issue requires a separate study, which must commence with an investigation of resources and trade patterns of copper, tin and lead in this part of Europe in the Late Middle Ages. A lot of information can be obtained from written sources. For instance, it is known that part of copper for the Teutonic *Grose Bochse* from 1408 came from Banská Bystrica (Besztercebánya) in Upper Hungary (present-day Slovakia) [51 p33] (on Upper Hungarian copper ore mines see, e.g., [84 p88]).

Conclusions And Suggestions For Further Research

The discussed cannon from Grodno is a very interesting example of early firearms from Eastern Europe. It seems to be a rather typical representative of light field cannons, both with regard to its morphology and the chemical composition of the alloy. Concerning the latter trait, attention is drawn to a high amount of Pb, which may have been added to the alloy in order to facilitate the casting process. On the basis of both archaeological and historical evidence as well as available analogies, the late 14th c. chronology of the artefact can be safely proposed. The cannon must have been related to the troops that participated in the hostilities over Grodno in the period in question. Its Teutonic manufacture could only speculatively be proposed and on the basis of available data nothing can be said on the provenance of its metal.

It can be hoped that technological examinations of medieval and modern period firearms will continue and more will be known on methods of their manufacture. Eventually, new technological analyses may also bring more data that would allow for more advanced provenance studies of old firearms. Concerning copper alloy gun manufacture in the Teutonic Order's state, a great research potential rests in archaeological finds from the foundry area at the Castle of Malbork (Marienburg). Furthermore, the metal of the Teutonic cannon from Kurzętnik (Kauernick) can be re-examined in order to obtain data on its chemistry. It is therefore highly recommended to carry on a provenance study on the Grodno gun with the most up-to-date scientific methods.

Abbreviations

SEM: Scanning electron microscopy; EDS: Energy dispersive spectoscopy; XRF: X-ray fluorescence

Declarations

Acknowledgements

The authors are obliged to Ms Natalia Kiziukevič, Head of the Archaeology Department of the State Historical and Archaeological Museum in Grodno, Belarus for valuable pieces of information concerning the find context, photographical documentation and samples of the cannon. Thanks must also go to Captain Yurii Kulikov from Crimea and to Dr Alexandr Strelčenko for their valuable remarks and help with access to Russian literature. Captain Kulikov was also kind enough to provide the authors with the drawings of the Stary Krym cannon.

Authors' contributions

PS and GŻ initiated this research and discussed the archaeological and historical contexts of the find. GŻ carried out sample preparation and microscopic observations, whereas TG and KA offered valuable remarks on the metal's microstructure. TG performed EDS analyses, while GŻ was responsible for data processing. EM-J provided important comments on the composition of archaeological copper alloys. All authors read and approved the final manuscript.

Funding

This work was not funded by any research project

Availability of data and materials

The raw data used in this manuscript is available as Electronic Supplement (Excel)

Ethnics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare no conflict of interest

Author details

[1] Institute of History, Jan Długosz University in Częstochowa, Poland

g.zabinski@gmail.com

ORCID: https://orcid.org/0000-0003-3091-1035

[2] Institute of Archaeology, Uniwersity of Łódź, Poland

piotr.strzyz@uni.lodz.pl

ORCID: https://orcid.org/0000-0001-6846-159X

[3] Institute of Materials Science, Silesian University, Katowice, Poland

tomasz.goryczka@us.edu.pl

ORCID: https://orcid.org/0000-0002-6405-2825

krzysztof.aniolek@us.edu.pl

ORCID: https://orcid.org/0000-0002-5382-2038

[4] National Centre for Nuclear Research, Świerk, Otwock, Poland

Ewelina.Mista@ncbj.gov.pl

ORCID: https://orcid.org/0000-0002-0053-8711

References

1. Davies J. The Medieval Cannon 1326-1494. New Vanguard 273. Oxford: Osprey Publishing; 2019.
2. Strzyż P. Broń palna w Europie Środkowej w XIV-XV w. (Firearms in Central Europe in the 14th-15th c.). Łódź: Polska Akademia Nauk, Instytut Archeologii i Etnologii; 2014.
3. McLachlan S. Medieval handgonnes. The first black powder infantry weapons. Osprey Weapon 3. Oxford: Osprey Publications; 2010.
4. Smith RD, DeVries K. The Artillery of the Dukes of Burgundy, 1363-1477. Woodbridge: Boydell Press; 2005.
5. Ashkenazi D, Cvikel D, Langgut D, Rosen B, Galili E. Artillery and rigging artefacts from the Megadim wreck-site, Israel. J Archaeol Sci.: Reports 2017;14:91-105. http://dx.doi.org/10.1016/j.jasrep.2017.05.031.
6. Mustaček M, Ćurković M, Jozić A, Jelić A. Appendix: The Conservation and Restoration of the Finds. In: C. Beltrame, S. Gelichi, I. Miholjek, editors. Sveti Pavao Shipwreck. A 16th Century Venetian Merchantman from Mljet, Croatia. Oxford: Oxbow Books; 2014. p. 154-166.
7. Smith RD. The technology of wrought-iron artillery. Royal Armouries Yearbook 2000;5:68-79.
8. Smith RD, Brown RR. Bombards Mons Meg and her sisters. Royal Armouries Monograph 1. London: Royal Armouries; 1989.
9. Żabiński G. Technology of manufacture of firearms in the Teutonic Order's state in Prussia – gun barrels and metal projectiles. Fasciculi Archaeologiae Historicae (From the Problems of Historical Archaeology) 2015;28:83-110. https://www.academia.edu/22614135. Accessed on 20 February 2021.
10. Żabiński G, Biborski M, Miśta-Jakubowska E. A late medieval or early modern light gun barrel from the Castle Museum in Malbork—typology, technology of manufacture and identification of the smelting process. Archaeol Anthropol Sci. 2019;11.5:2007-2026. https://doi.org/10.1007/s12520-018-0653-3.
11. Żabiński G, Biborski M, Biborski M, Stępiński J, Miśta-Jakubowska E. A late medieval or early modern ferrous hackbut barrel from the collection of the Castle Museum in Malbork. Acta Militaria Mediavalia 2018;14:175-207.
12. Volkau MA. Arhitektura Staroga zamka y Grodna y XVI-XVIII stst.: vzglyad i pryznačenne zbydavannyau razmešč uzdouž niomanskay scyany (Architecture of Old Castle in Grodno in the 16th-18th c.: view and functions of buildings along the Neman wall). Belaruski gistaričny časopis 2015;11:5-22. https://www.academia.edu/19861677. Accessed on 15 February 2021.

13. Volkau MA. Arhitektura Staroga zamky časou Vitauta u Garodni (Architecture of Old Castle in Grodno in the times of Vytautas). Belaruski gistaričny časopis 2014;2:17-34. https://www.academia.edu/6225236. Accessed on 15 February 2021.
14. Volkau MA. Ab nekatoryh aspektah arhitektury Staroga zamka u Garodni časou Stefana Batorya (Some aspects of the architecture of the Old Castle in Grodno in the times of Stephen Báthory). Krayauznayčya zapiski 2013;9:16-20. https://www.academia.edu/7631863. Accessed on 15 February 2021.
15. Durczewski Z. Stary zamek w Grodnie w świetle wykopalisk dokonanych w latach 1937-1938 (Old Castle in Grodno in the light of excavations carried out in 1937-1938). Grodno: Wojewódzki Komitet Uczczenia Króla Stefana Batorego w Grodnie; 1939.
16. Wigand von Marburg. Die Chronik Wigands von Marburg. In: T Hirsch, editor. Scriptores Rerum Prussicarum 2. Lepizig: Verlag von S. Hirzel; 1863. p. 429-662.
17. Franciscani Thorunensis Annales Prussici (941-1410). In: E Strehlke, editor. Scriptores rerum Prussicarum 3. Leipzig: Verlag von S. Hirzel; 1866. p. 13-399.
18. Nikodem J. Witold wielki książę litewski (1354 lub 1355 – 27 października 1430) (Vytautas Grand Duke of Lithuania, 1354 or 1355 – 27 October 1430). Kraków: Avalon; 2013.
19. Posilge J. Johanns von Posilge, Officials von Pomesanien, Chronik des Landes Preussen (von 1360 an, fortgesetzt bis 1419) zugleich mit den auf Preussen bezuglichen Abschnitten aus der Chronik Detmar's von Lübeck. In: E Strehlke, editor. Scriptores rerum Prussicarum 3. Leipzig: Verlag von S. Hirzel; 1866. p. 13-399.
20. Długosz J. Johannis Dlugosii Annales seu Cronicae Incliti Regni Poloniae. Liber X 1370-1405. Editors S. Gawęda, A. Kamiński, M. Kowalczyk, S. Kozłowska-Budkowa, S. Mikucki, J. Mitkowski, S. Perzanowski, C. Pieradzka, M. Plezia, D. Turkowska, W. Semkowicz-Zarembina. Varsaviae: Państwowe Wydawnictwo Naukowe; 1985.
21. Stępiński J, Żabiński G, Strzyż P. The light field cannon from Kurzętnik – a unique example of medieval artillery (against the background of development of firearms in the Teutonic Order's state in Prussia). Acta Militaria Mediaevalia 2013;9:155-202. https://www.academia.edu/22454250. Accessed on 21 February 2021.
22. Die Ältere Hochmeisterchronik. In: M Toeppen, editor. Scriptores Rerum Prussicarum 3. Leipzig: Verlag von S. Hirzel; 1866. p. 519-709.
23. Schmidtchen V. Die Feuerwaffen des Deutschen Ritterordens bis zur Schlacht bei Tannenberg 1410: Bestände, Funktion und Kosten, dargestellt anhand der Wirtschaftsbücher des Ordens von 1374 bis 1410. Lüneburg: Nordostdeutsches Kulturwerk; 1977.
24. Szymczak J. Początki broni palnej w Polsce 1383-1533 (Beginnings of firearms in Poland 1383-1533). Łódz: Wydawnictwo Uniwersytetu Łódzkiego; 2004.
25. Świętosławski W. Koszt broni palnej i jej użycia w państwie krzyżackim w Prusach na początku XV wieku (Costs of firearms and their use in the Teutonic Order's state in Prussia in the beginning of the 15th c.). Studia i materiały do historii wojskowości 1993;35:19-31.
26. Prodolzene letopisi po Voskresenskomu spisku. In: Polnoe sobrane russkih letopisey Vol. 8. Sankt Petersburg: Tipografia Eduarda Praca; 1859.
27. Novgorodskaya četvertaya letopis. In: Polnoe sobrane russkih letopisey. Vol. 4.1. 2nd ed. Leningrad: Izdatelstvo Akademii Nayk SSSR; 1925.
28. Letopisny sbornik imenuemy Patriaršeyu ili Nikonovskoyu letopisyu. In: Polnoe sobrane russkih letopisey Vol. 11. Sankt Petersburg: Tipografia I. N. Skorohodova; 1897.
29. Letopisny sbornik, imenuemy Tverskoyu letopisyu. In: Polnoe sobrane russkih letopisey Vol. 15. Sankt Petersburg: Tipografia Leonida Demisa; 1863.
30. Novgorodskye i pskovskye letopisi. In: Polnoe sobrane russkih letopisey Vol. 4. Sankt Petersburg: Tipografia Eduarda Praca; 1848.
31. Ulyanov OG. Drevneyšy arsenal w Moskovskom Kremle – mesto roždenya russkoy artilerii. In: Voina i oruže. Novye issedovanya i materialy. Trudy V meždunarodnoy naučno-praktičeskoy konferencii 14-16 maya 2015 g. Part 4. Sankt Petersburg: Voenno-istoričeski muzey artilerii, inženernyh voisk i voisk svyazi; 2015. p. 220-243.
32. Kirpičnikov AN. Voennoe delo na Rusi v XIII-XV vv. Leningrad: Izdatelstvo Nauka; 1976.
33. Wilinbachow W. Początkowy okres rozwoju broni palnej w krajach słowiańskich (Initial period of development of firearms in Slavic countries). Kwartalnik Historii Nauki i Techniki 1963;8.2:215-235.
34. Kulikov Y. Ouery – Cannons in the Crimea. Ordnance Society Newsletter October 2016;115:27-28.
35. Pskovskaya vtoraya i Sofiyskaya pervaya letopis. In: Polnoe sobrane russkih letopisey Vol. 5. Sankt Petersburg: Tipografia Eduarda Praca; 1851.
36. Letopisny sbornik, imenuemy letopisyu Avraamki. In: Polnoe sobrane russkih letopisey Vol. 16. Sankt Petersburg: Tipografia E. Eneopskogo i K°; 1889.

37. Dopolnenya k aktam istoričeskim, sobrannya i izdannya arheologičeskoyu kommisyeu. Vol. 5. Sankt Petersburg: V tipografii Eduarda Praca; 1853.
38. Kulikov Y. Istoria vozniknoenya artilerii i pervye artilleriyskye orudya v Krymu. Military Krym. Voensko-istoričeski žurnal 2017;31.1:59-62.
39. Malčenko O. Museum artilleriae ucrainicae saeculi XV-XVIII pars prima. Kiovia: Institut Ukrainskoi Arheografii ta Džereloznavstva Narodnoi Akademii Nauk Ukrainy; 2011.
40. Makovskaya LK. Ručnoe ognestelnoe oruže russkoy armii konca XIV-XVIII v. Moskva: Voennoe Izdatelstvo; 1992.
41. Milyaev PA. Nahodki detaley ručnogo ognestelogo vooruženya vtoroy poloviny XV-XVI v. iz Staroy Ladogi i kreposti Orešek v svete vostočno- i zapadnoevropeiskih analogii. Arheologičeske vesti 2018;24:218-238.
42. Strzyż P. Broń palna w Polsce średniowiecznej. Studium archeologiczne (Firearms in medieval Poland. An archaeological study). Łódź: Polska Akademia Nauk, Instytut Archeologii i Etnologii; 2011.
43. **Lazar T. The oldest preserved gun in Slovenia. In: G Oitzl, A Miškec, editors. The Past under the Microscope. Scientific Analyses in Museums. Ljubljana: Narodni Muzej Slovenije; 2018. p 86-96.**
44. Lazar T. Poznosrednjeveško topništvo na Slovenskem. Raziskave dveh zgodnjih topov iż Pokrajinskega muzeja Ptuj – Ormož (Late-medieval artillery in Slovenia. A study of two early artillery pieces from the Regional Museum Ptuj – Ormož). Ljubljana: Narodni Muzej Slovenije; 2015.
45. Postică G. Două tunuri de bronz din perioada lui Ştefan cel Mare descoperite în cetatea Orheiului Vechi (Two bronze cannons from the period of Stefan the Great discovered in the town of Orheiul Vechi). Arheologia Moldovei 2004;27:165-176.
46. Ilijić G. Nalazi topova sa prostora Beogradske tvrćave kao svedočanstva ugarsko-turskih borbi za Beograd (Cannon finds from the Fortress of Belgrade as a testimony of the Hungarian-Turkish fights for Belgrade). Vesnik 2009;36:18-28.
47. Popović M. Beogradska tvrdjava (The fortress of Belgrade). 2nd ed. Beograd: Javno Preduzece "Beogradska Tvrdava"; 2009.
48. Anleitung, Schiesspulver zu bereiten Büchsen zu laden und zu beschiessen (c. 1400/1410). Bayerische Staatsbibliothek, München, Cgm 600. https://daten.digitale-sammlungen.de/~db/0011/bsb00113907/images/. Accessed 2 February 2021.
49. Das Buch von der Büchsenmeisterei (1462/1463), Germanisches Nationalmuseum, Nürnberg, Hs 719. http://dlib.gnm.de/item/Hs719/1. Accessed 1 August 2020.
50. Zeugbuch Kaiser Maximilians I (c. 1502). Innsbruck. Bayerische Staatsbibliothek München, Cod. Icon. 222. https://daten.digitale-sammlungen.de/~db/0002/bsb00020956/images/. Accessed 30 May 2015.
51. Żabiński G. The Grose bochse – a Teutonic Supergun from 1408. Fasciculi Archaeologiae Historicae 2012;25:31-40. https://www.academia.edu/3557136. Accessed 21 February 2021.
52. Williams AR, Paterson AJR. A Turkish bronze cannon in the Tower of London. Gladius 1986;17:185-205. http://gladius.revistas.csic.es/index.php/gladius/article/view/122/122. Accessed 10 May 2020.
53. Biringuccio V. The Pirotechnia of Vannoccio Biringuccio. The Classic Sixteenth-Century Treatise on Metals and Metallurgy. Translated and edited by C. S. Smith and M. Teach Gnudi (an unabridged republication of the 1959 edition by The American Institute of Mining and Metallurgical Engineers, Inc.; original edition: De la pirotechnia. Libri X. C. Navò, Venetia 1540). Mineola-New York: Dover Publications; 2005.
54. Dąbrowska M. Proces odlewania dział w lejni malborskiej w XV wieku (Process of gun casting at the Malbork foundry in the 15th c.). Archaeologia Historica Polona 2009;18:21-44.
55. Dąbrowska M. Badania archeologiczno-architektoniczne na terenie Zamku Niskiego w Malborku w latach 1998-2004 (Archaeological-architectural research in the area of the Low Castle in Malbork in 1998-2004). In: G Nawrolska, editor. XV Sesja Pomorzoznawcza. Materiały z konferencji 30 listopada-2 grudnia 2005 r. (15th Session of Studies on Pomerania). Conference proceedings, 30 November-2 December 2005). Elbląg: Muzeum Archeologiczno-Historyczne w Elblągu; 2007. p. 303-316.
56. Belényesy K. Cannon foundry workshop in late medieval Buda (Hungary) at the turn of the 15th-16th centuries. In: Thomas N, Dandridge P, editors. Cuivre, bronzes et laitons médiévaux: Histoire, archéologie et archéométrie des productions en laiton, bronze et autres alliages à base de cuivre dans l'Europe médiévale (12e-16e siècles). Medieval copper, bronze and brass: History, archaeology and archaeometry of the production of brass, bronze and other copper alloy objects in medieval Europe (12th-16th centuries). Actes du colloque de Dinant et Namur, 15-17 mai 2014. Proceedings of the symposium of Dinant and Namur, 15-17 May 2014. Études et documents, Archéologie 39. Namur: Agence wallonne du Patrimoine; 2018. p. 155-167.
57. Antoni D. The Oldest Hand-held Firearms from Slovakia. Studia Universitatis Cibiniensis. Series Historica 2013;10:111-127.
58. Rathgen B. Das Geschütz im Mittelalter. Berlin: VDI-Verlag; 1928.

59. Głosek M. Broń palna (Firearms). In: A Nadolski, editor. Uzbrojenie w Polsce średniowiecznej 1350-1450 (Arms and Armour in Medieval Poland 1350-1450). Łódź: Polska Akademia Nauk, Instytut Historii Kultury Materialnej; 1990. p. 155-178.
60. Ansani F. The Life of a Renaissance Gunmaker. Bonaccorso Ghiberti and the Development of Florentine Artillery in the Late Fifteenth Century. Technology and Culture 2017:58:749-789.
61. **Lazar T. The Slovenian lands as the armed frontier of the Holy Roman Empire. Fasciculi Archaeologiae Historicae 2017;30: 59-72.**https://doi.org//10.23858/FAH30.2017.006.
62. Lazar T. Oborožitev slovenskih dežel v začetku 16. stoletja: münchenski rokopis Cod.icon. 222 (Armament of Slovene Lands in the Early Sixteenth Century: The Munich Manuscript Cod.icon. 222). Zgodovinski časopis 2017;71:106-162.
63. Scott D, Schwab R. Metallography in Archaeology and Art. Cultural Heritage Science. Springer; 2019. https://doi.org/10.1007/978-3-030-11265-3.
64. Buchwald VF. Iron and steel in ancient times. Historisk-filosofiske Skrifter 29. Copenhagen: The Royal Danish Academy of Sciences and Letters; 2005.
65. Valério P, Monge Soares A, Araújo MF, Silva RJC, Porfírio E, Serra M. Arsenical copper and bronze in Middle Bronze Age burial sites of southern Portugal: the first bronzes in Southwestern Iberia. J Archaeol Sci. 2014;42:68-80. http://dx.doi.org/10.1016/j.jas.2013.10.039.
66. Mihajlovič I. 4.2. The Ordnance. In: C Beltrame, S Gelichi, I Miholjek, editors. Sveti Pavao Shipwreck. A 16th Century Venetian Merchantman from Mljet, Croatia. Oxford: Oxbow Books; 2014. p.53-63.
67. Morin M. Morphology and constructive techniques of Venetian artilleries in the 16th and 17th centuries: some notes. In: C Beltrame, RG. Ridella, editors. Ships & Guns. The sea ordnance in Venice and Europe between the 15th and the 17th centuries. Oxford: Oxbow Books; 2011. p 1-11.
68. Bourgarit D, Thomas N. Late medieval copper alloying practices: a view from a Parisian workshop of the 14th century AD. J Archaeol Sci. 2012;39:3052-3070. https://doi.org/10.1016/j.jas.2012.04.009.
69. Pernicka E. Provenance determination of archaeological metal objects. Memorie del Museo Civico di Storia Naturale di Verona. 2. serie. Sezione Scienze dell'Uomo 2011;11:27-37. http://archiv.ub.uni-heidelberg.de/propylaeumdok/4720/1/Pernicka_Provenance_determination_2011.pdf. Accessed on 17 February 2021.
70. Pernicka E. Chapter 11: Provenance determination of archaeological metal objects. In: BW Roberts, C Thornton, editors. Archaeometry in Global Perspectives. Methods and Syntheses. Springer; 2014, p. 239-268. DOI: 10.1007/978-1-4614-9017-3_11.
71. Pollard AM, Bray P. A New Method for Combining Lead Isotope and Lead Abundance Data To Characterize Archaeological Copper Alloys. Archaeometry 2015;57.6:999-1008. https://doi.org/10.1111/arcm.12145.
72. Hauptmann A, Schmitt-Strecker S, Begemann F, Palmieri A. Chemical Composition and Lead Isotopy of Metal Objects from the "Royal" Tomb and Other Related Finds at Arslantepe, Eastern Anatolia. Paléorient 2002;28:43-69. https://doi.org/10.3406/paleo.2002.4745.
73. Niederschlag E, Pernicka E, Seifert Th, Bartelheim M. The determination of lead isotope ratios by multiple collector ICP-MS: a case study of early Bronze Age artefacts and their possible relation with ore deposits of the Erzgebirge. Archaeometry 2003;45:61-100. DOI: 10.1111/1475-4754.00097.
74. Lutz J, Pernicka E. Prehistoric copper from the Eastern Alps. Open Journal of Archaeometry 2013; 1:e25:122-127. https://doi.org/10.4081/arc.2013.e25.
75. Artioli G, Angelini I, Tecchiatti U, Petrotti A. Eneolithic copper smelting slags in the Eastern Alps: local patterns of metallurgical exploitation in the Copper Age. J Archaeol Sci. 2015;63:78-83. https://doi.org/10.1016/j.jas.2015.08.013.
76. Artioli G, Angelini I, Nimis P, Villa IM. A lead-isotope database of copper ores from the Southeastern Alps: a tool for the investigation of prehistoric copper metallurgy. J Archaeol Sci. 2016;75:27-39. https://doi.org/10.1016/j.jas.2016.09.005.
77. Pryce TO, Baron S., Bellina BHM, Bellwood PS, Chang N, Chattopadhyay P, Dizon E, Glover IC, Hamilton E, Higham CFW, Kyaw AA, Natapintu S, Nguyen V, Pautreau JP, Pernicka E, Pigott VC, Pollard M, Pottier C, Reinecke R, Sayavongkhamdy T, Souksavatdy V, White J. More questions than answers: the Southeast Asian lead isotope project 2009–2012. J Archaeol Sci. 2014;42.1:273–294. https://doi.org/10.1016/j.jas.2013.08.024.
78. Pollard A, Bray P, Cuénod A, Hommel P, Hsu Y, Liu R, Perucchetti L, Pouncett J, Saunders M. Previous Approaches to the Chemistry and Provenance of Archaeological Copper Alloys. In: iid. Beyond Provenance: New Approaches to Interpreting the Chemistry of Archaeological Copper Alloys. Leuven: Leuven University Press; 2018. p. 13-40. https://doi.org/10.2307/j.ctv7xbs5r.4.
79. Rademakers FW, Rehren T, Pernicka E. Copper for the Pharaoh: identifying multiple metal sources for Ramesses' workshops from bronze and crucible remains. J Archaeol Sci. 2017;80:50-74. http://dx.doi.org/10.1016/j.jas.2017.01.017.
80. Siklósi Z, Szilágyi M. New data on the provenance of copper finds from the Early-Middle Copper Age of the Great Hungarian Plain. Archaeol Anthropol Sci. 2019;11.10:5275-5285. https://doi.org/10.1007/s12520-019-00867-8.

81. Nørgaard HW, Pernicka E, Vandkilde H. On the trail of Scandinavia's early metallurgy: Provenance, transfer and mixing. PLoS ONE 2019;14(7): e0219574. https://doi.org/10.1371/journal.pone.0219574.
82. Kowalski Ł, Garbacz-Klempka A, Gackowski J, Ścibiór D, Perek-Nowak M, Adamczak K, Długosz P. Towards direct casting: Archaeometallurgical insight into a bronze mould from Elgiszewo, Poland, 900–700 BC. Archeol Rozhl. 2019;71:45-66. https://www.arup.cas.cz/wp-content/uploads/2020/10/03_Kowalski_45-66_web.pdf. Accessed on 19 February 2021.
83. Radivojević M, Roberts BW, Pernicka E, Stos-Gale Z, Martinón-Torres M, Rehren T, Bray B, Brandherm D, Ling J, Mei J, Vandkilde H, Kristiansen K, Shennan SJ, Broodbank C. The Provenance, Use, and Circulation of Metals in the European Bronze Age: The State of Debate. Jour Archaeol Res. 2019;27:131-186. https://doi.org/10.1007/s10814-018-9123-9.
84. Tylecote RF. A History of Metallurgy. 2nd ed. London: Maney Publishing; 1992.
85. 85. Mäll J. Otepää piiskopilinnuselt leitud varspüssi rekonstrueerimine (Reconstruction of a handgonne found at the Otepää Episcopal Castle). In Ü Tamla, V. Lang, editors. Ilusad asjad: tähelepanuväärseid leide Eesti arheoloogiakogudest (Beautiful things. Significant artefacts from the archaeological collections in Estonia). Tallinn: Tallinna Ulikooli Ajaloo Instituut; 2010. p. 193-210.
86. Skála J, Waldhauser J. Nález palné zbraně vrcholného středověku na tvrzišti Rakově na okrese Jičin v historickém kraji boleslavském (Discovery of a high medieval firearm in the fortress of Rakov in the Jičin district in the historical land of Boleslav). Castellologica Bohemica 2000:7:309-313.
87. Stránský K, Ustohal V. Rozměrová and materiálová analýza hákovnice a píšťaly (A metrical and material analysis of the hackbut and the handgonne. In: Z Měřínský, R Nekuda. Dva nové nálezy pozůstatků ručních palných zbraní z Moravy (předběžná zpráva) (Two new finds of remains of firearms in Moravia (a preliminary report). Castellologica Bohemica 1993:3:277-288.
88. Chmielowiec S, Kašpar V, Waldhauser J. Fragment palné zbraně z hradu Valečova v Pojizeří (Fragment of a firearm from the Castle of Valečov in Pojizeře). Archeologie ve středních Čechăch 2013;17:745-757.
89. Miazga B. Wyniki badań rentgenofluoresencyjnych fragmentu lufy z zamku Karpień (Results of XRF examinations of a barrel fragment from Castle Karpień). Acta Militaria Mediaevalia 2010;6:117-120.
90. Nekuda R, Kukla Z. Zbraně, jimiž byla ostřelována tvrz ve Mstěnicích (Firearms used in bombarding the fortress in Mstěnice). In: P Kouřil, R Nekuda, J Unger, editors, Ve službách archeologie Sborník k 60.\narozeninám RNDr. Vladimíra Haška, DrSc. (In the service of archaeology. A Festschrift to RNDr. Vladimír Hašek, DrSc.). Brno: Archeologický ústav AV ČR Brno; 1998. p. 223–228.
91. Smith RD. A 16th century Portuguese bronze breech-loading swivel gun. Militaria. Revista de Cultura Militar 1995;7:197-205.
92. Os B van, Huisman H, Vos A, Dijk L van, Nienhuis J, Joosten I. 17th century bronze cannon: How can they be magnetic? In: RB Scott, D Braekmans, M Carremans, P Degryse, editors. Proceedings of the 39th International Symposium for Archaeometry. Centre for Archaeological Science. Leuven: Leuven University Press; 2012; p. 135-138.

Figures

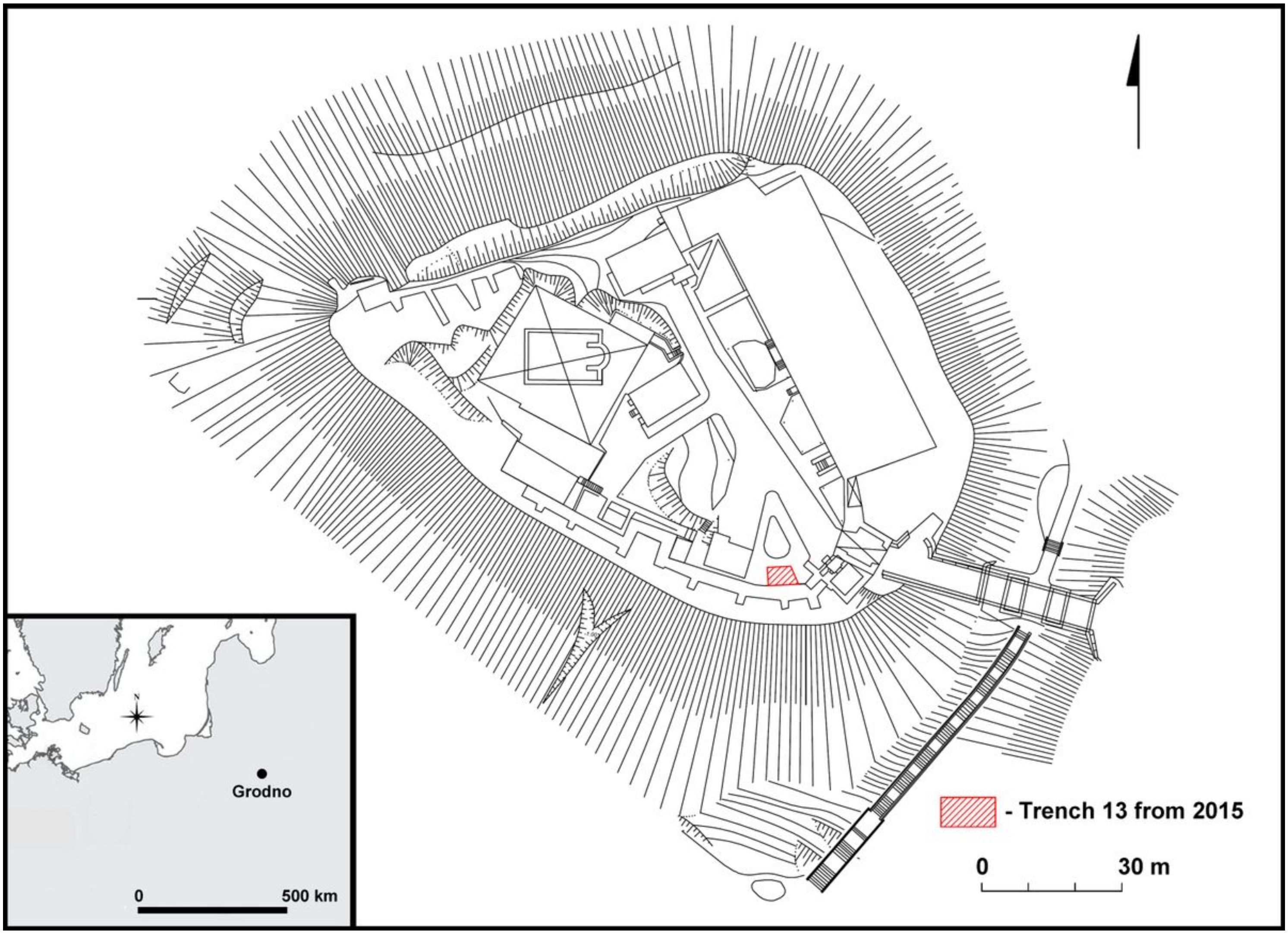

Figure 1

Old Castle in Grodno – location of Trench 13 on the castle's plan. Drawing N. Kiziukevič, adapted by G. Żabiński

Figure 2

Fragmented cannon from the Old Castle in Grodno in situ. Photo N. A. Kiziukevič

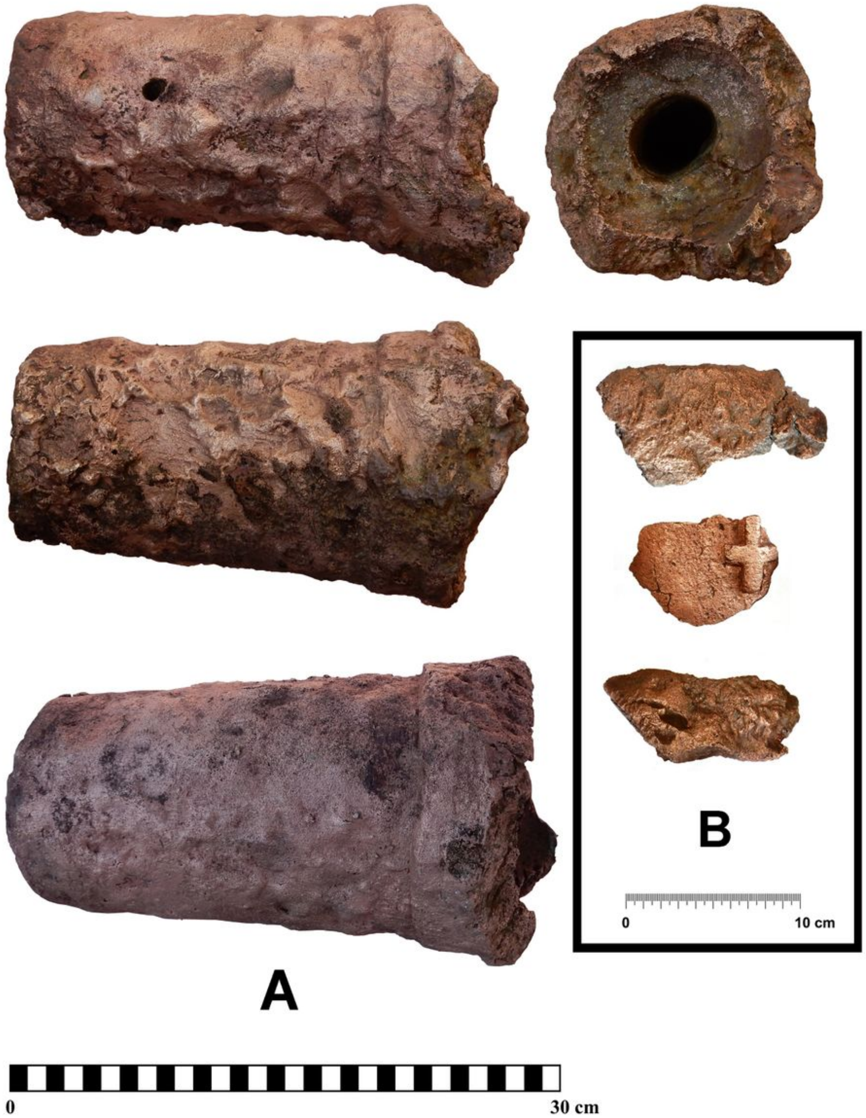

Figure 3

Cannon from the Old Castle in Grodno – A) present state of preservation; B) loose fragments, including the one ornamented with the cross.

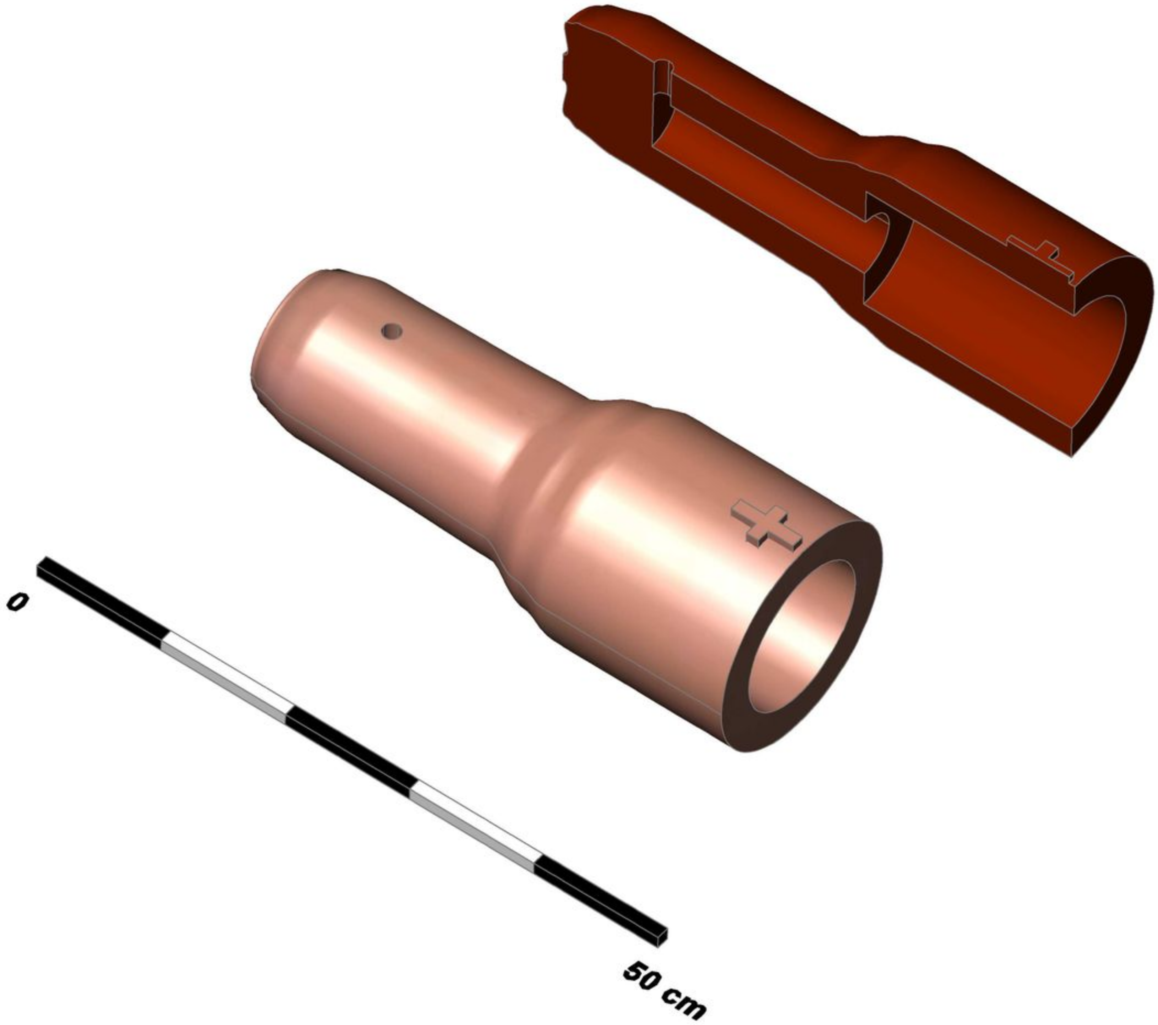

Figure 4

Cannon from the Old Castle in Grodno – speculative reconstruction and the cross-section.

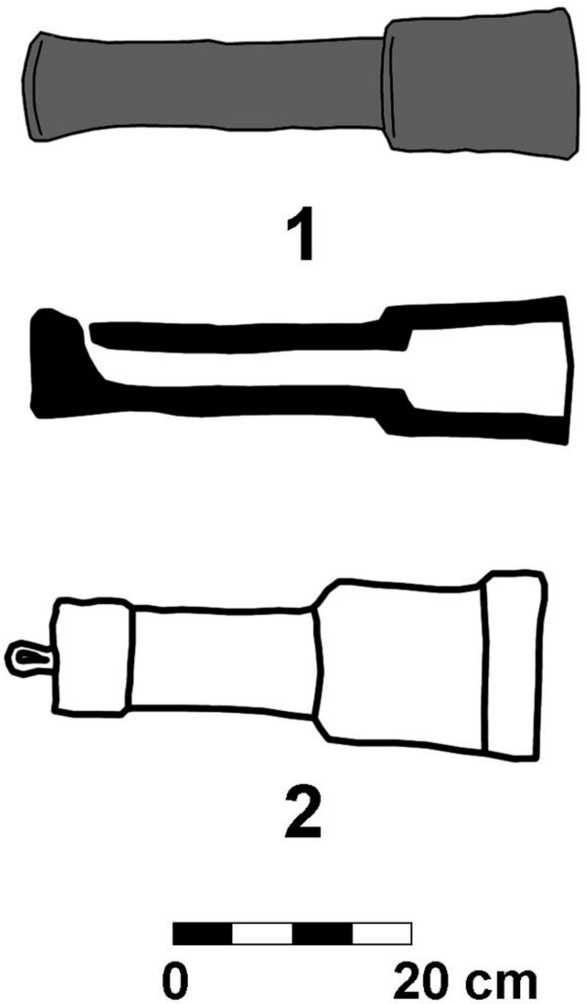

Figure 5

Early cannons in Russian collections: 1) mortira from Stary Krym, Crimea, Military-Historical Museum of Artillery, Engineers and Signal Corps, St. Petersburg, inv. No. 9/7; 2) “tyufyak” from Ržev, Tver State United Museum, Tver. After [33 p229, Fig. 6]. Afterdrawing G. Żabiński.

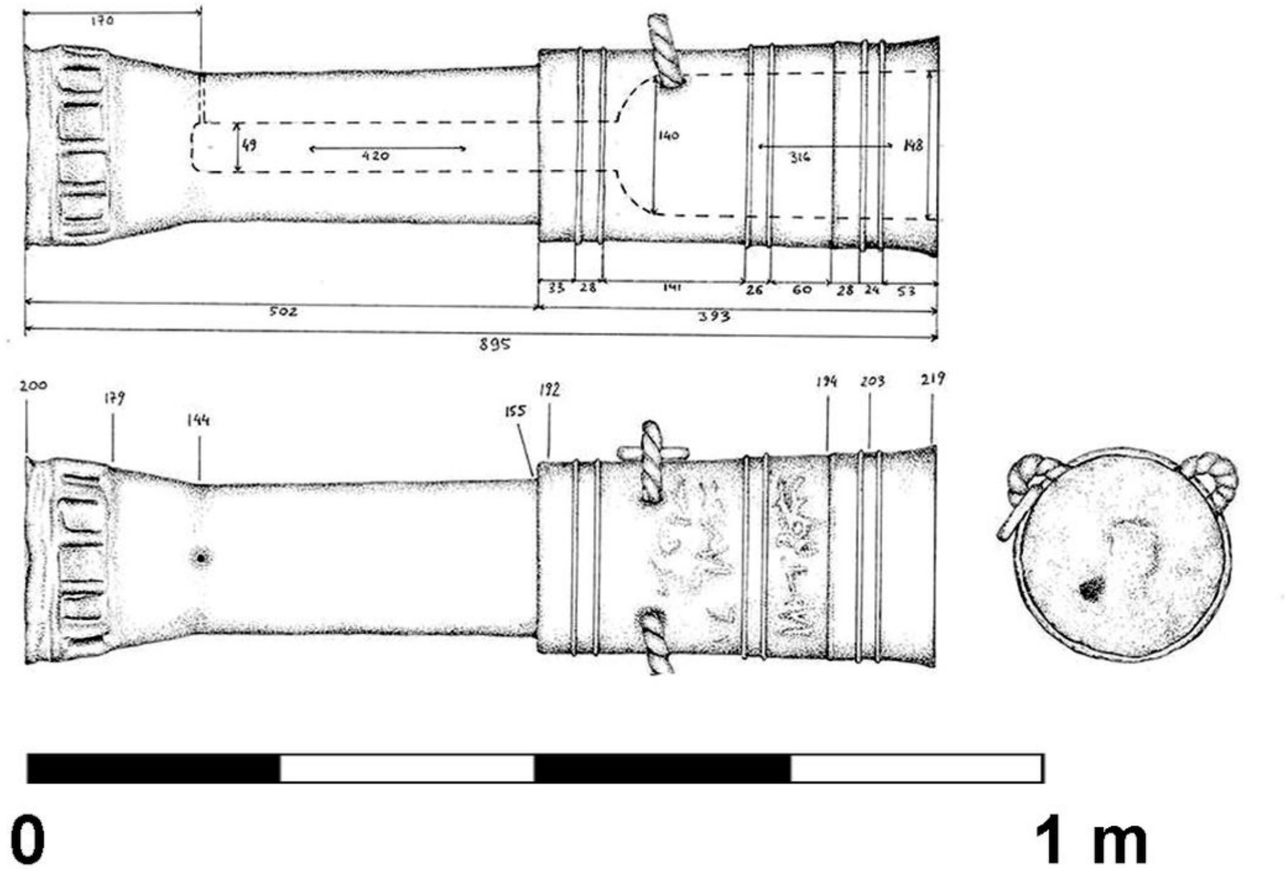

Figure 6

Light cannon from Stary Krym, Museum of Antiquities in Feodosia. Drawing O. Malčenko. After [34 p27, Fig. 2; 38 p61, Fig. 4]. Courtesy Captain Yurii Kulikov.

Figure 7

Light field cannon from Kurzętnik. G. Żabiński.

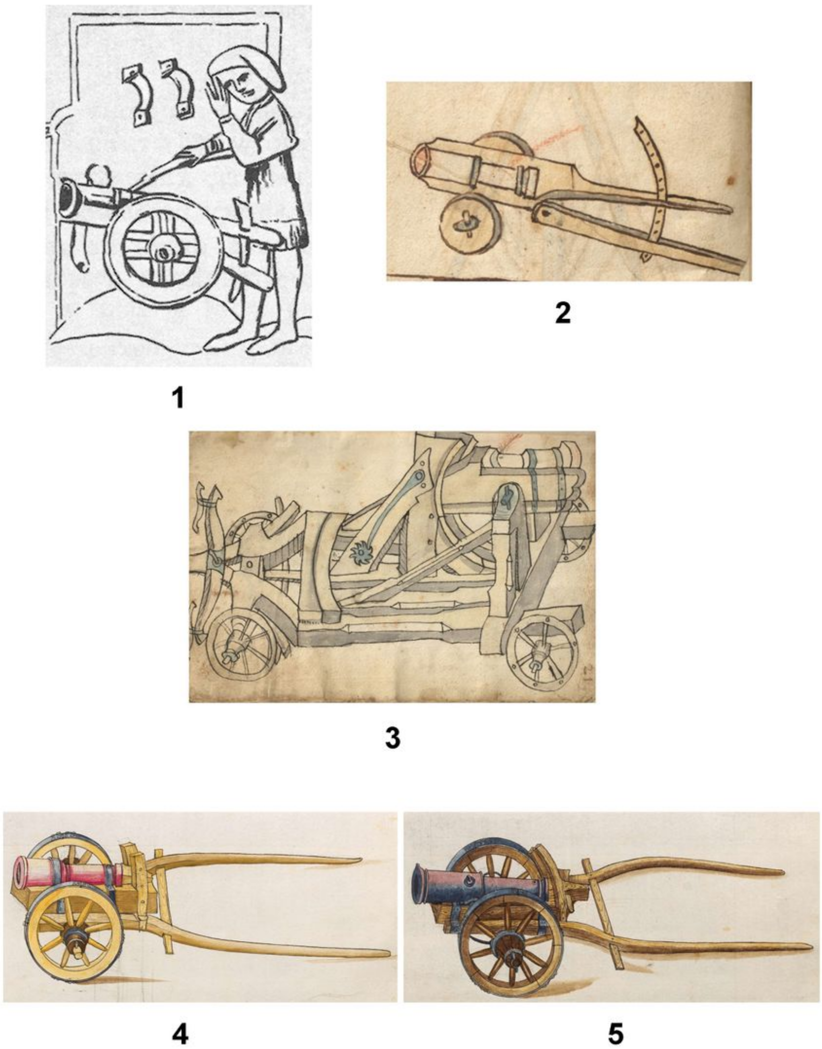

Figure 8

Light field cannons in late medieval and early modern period manuscripts – selected examples: 1) [48]. Copyright Bayerische Staatsbibliothek München; 2) [49, p32v]. Copyright Germanisches Nationalmuseum Nürnberg; 3) [49, p21r]. Copyright Germanisches Nationalmuseum Nürnberg; 4) [50, p187v]. Copyright Bayerische Staatsbibliothek München; 5) [50 p188v]. Copyright Bayerische Staatsbibliothek München.

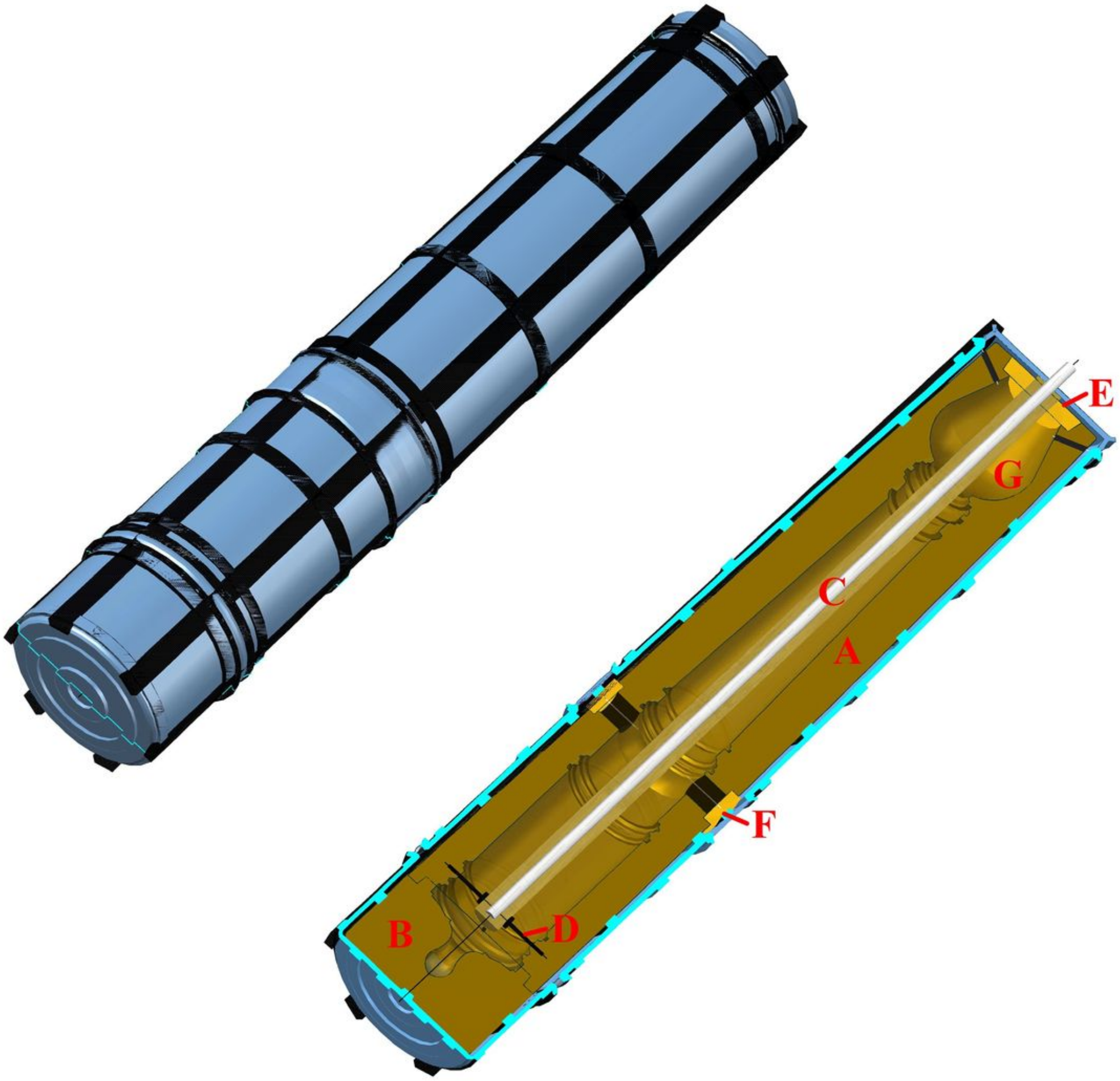

Figure 9

A reconstruction of the gun mould. After [9 p98, Fig. 1]. A – main body mould; B – breech mould; C – core; D – iron chaplets holding the core; E – clay disc holding the core; F – bricks closing the trunnion cavities; G – feeding head

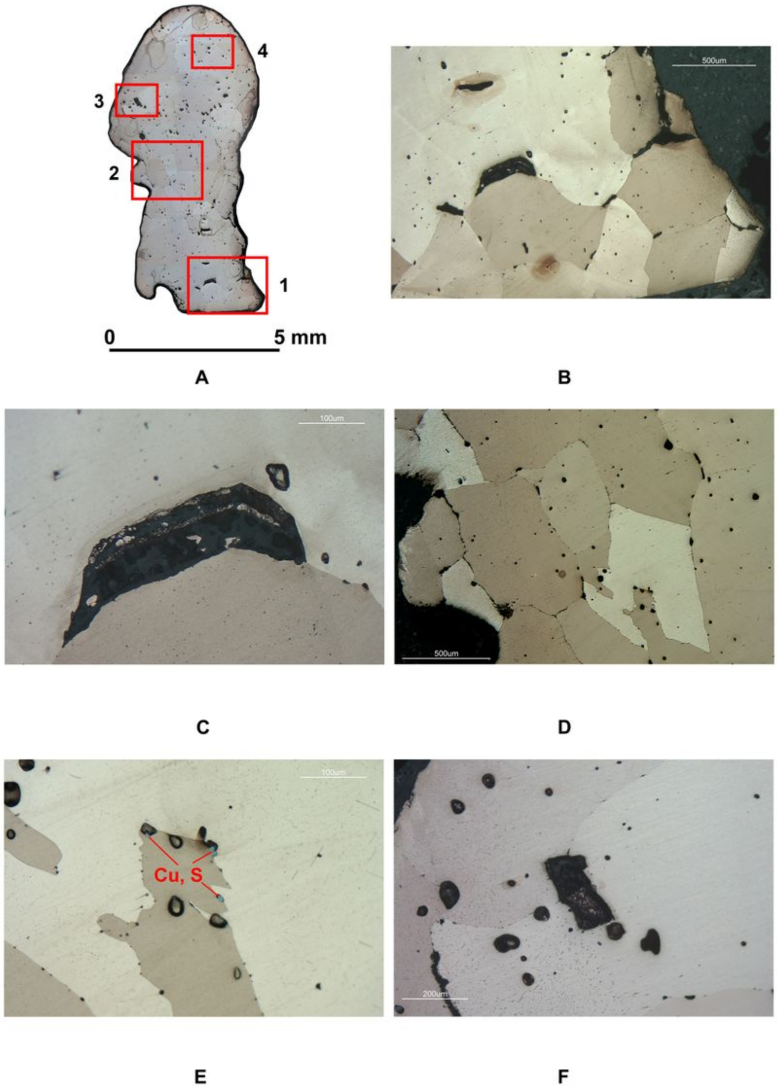

Figure 10

Cannon from Old Castle in Grodno, Sample 1 – results of metallographic examinations a) general view of the sample with zones of detailed observations (1-4) b, c) microstructure in Zone 1, pores of various size and shape d, e) microstructure in Zone 2, CuS inclusions (light blue) in the Cu-Pb matrix f) microstructure in Zone 3, numerous pores

Figure 11

Cannon from the Old Castle in Grodno, Sample 1 – results of metallographic examinations a, b) microstructure in Zone 4, numerous pores and an isolated CuS inclusion (light blue) in the Cu-Pb matrix

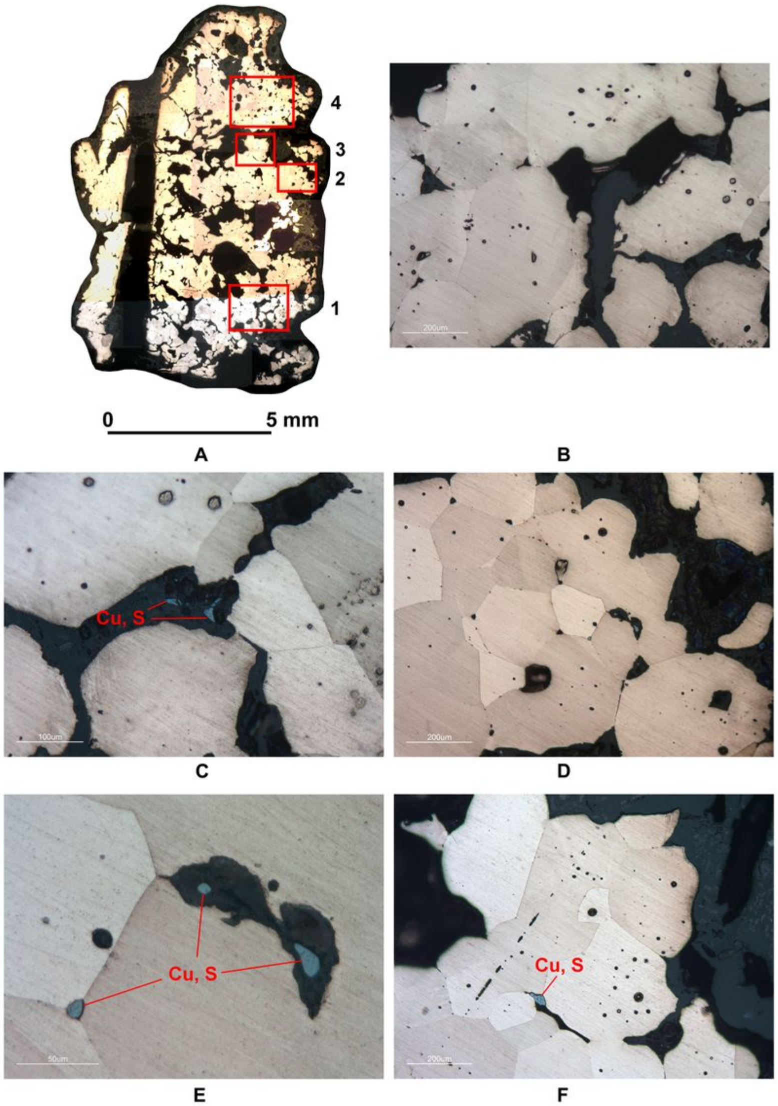

Figure 12

Cannon from Old Castle in Grodno, Sample 4 – results of metallographic examinations a) general view of the sample with zones of detailed observations (1-4) b, c) microstructure in Zone 1, pores of various size and shape, sometimes with CuS inclusions (light blue) d, e) microstructure in Zone 2, pores of various size and shape, sometimes CuS inclusions (light blue) f) microstructure in Zone 3, pores and a CuS inclusion (light blue)

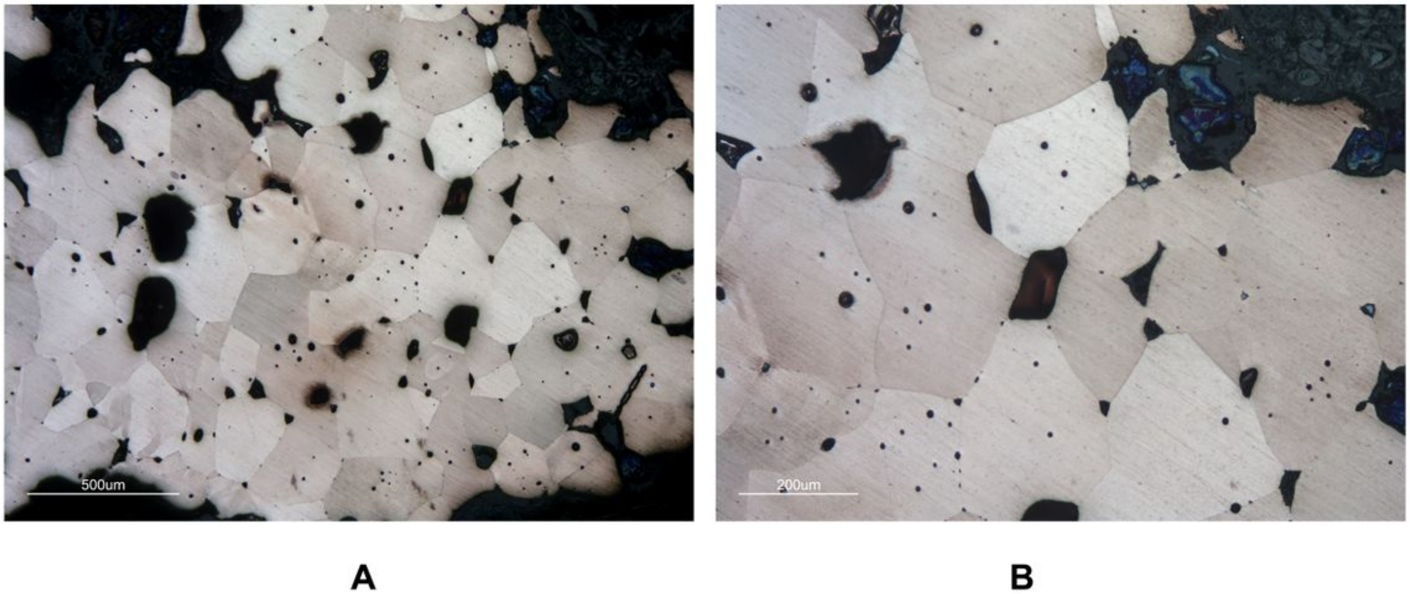

Figure 13

Cannon from Old Castle in Grodno, Sample 4 – results of metallographic examinations a, b) microstructure in Zone 4, numerous pores

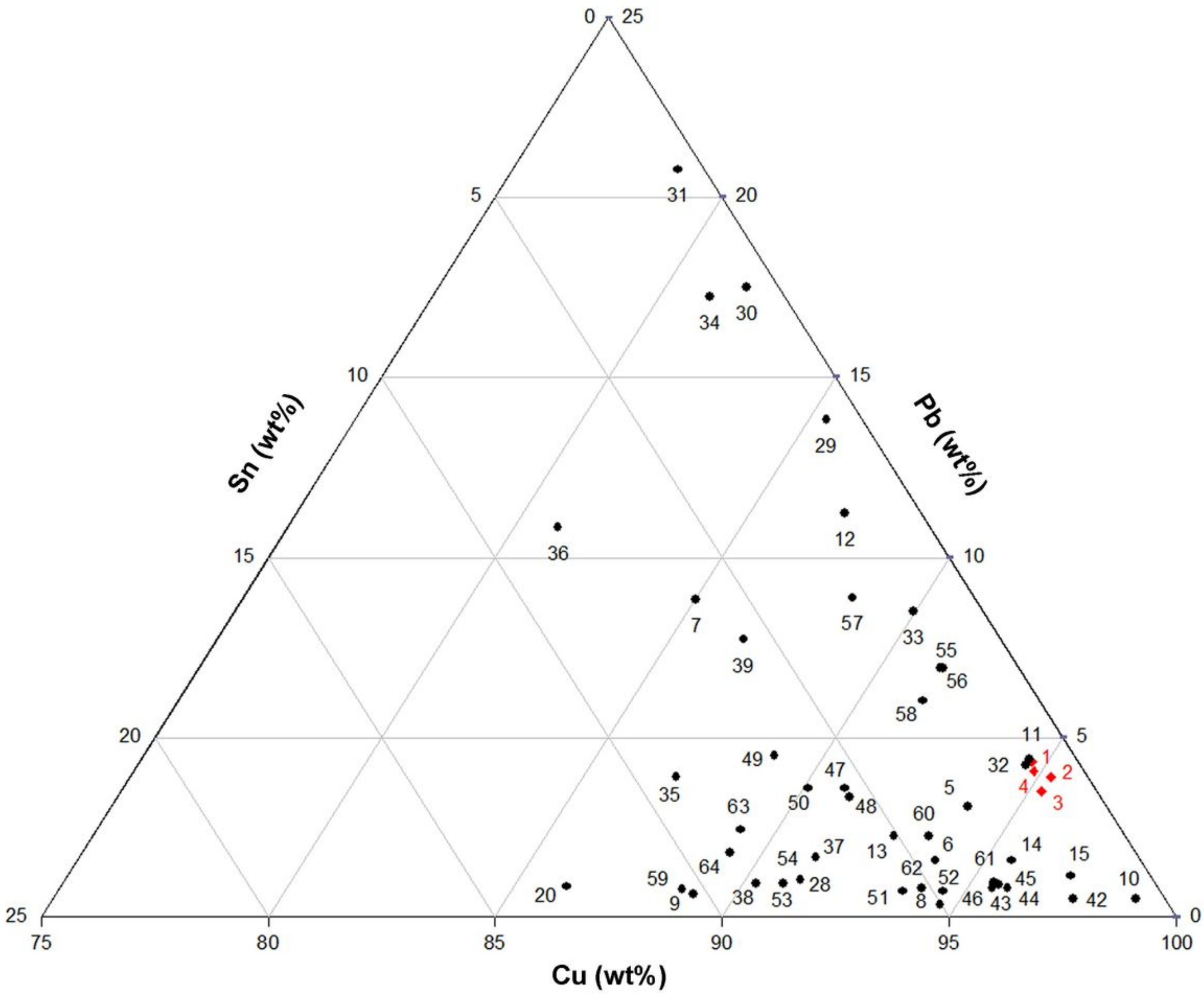

Figure 14

Cu-Pb-Sn ternary graph of the Grodno cannon against the background of comparative data. Legend: 1-4 – Grodno, Rus; 5 – Loshut, Sweden; 6 – Otepää, Livonia; 7 – Kalisz, Greater Poland; 8 – Rakov, Bohemia; 9 – Rokštejn, Moravia; 10 – Wenecja, Greater Poland; 11 – Valečov, Bohemia; 12 – Karpenstein, Silesia; 13 – Smederovo, Serbia, 14 – Gun 1, Mstěnice, Moravia; 15 – Gun 2, Mstěnice, Moravia; 20 – Grose Bochse, Marienburg, Teutonic Order; 28 – Cannon 1, Sv Pavao wreck, Mljet, Croatia; 29-31 – Cannon 2, Sv Pavao wreck, Mljet, Croatia; 32-34 – Cannon 2, Sv Pavao wreck, Mljet, Croatia; 35 – Cannon 4, Sv Pavao wreck, Mljet, Croatia; 36 – Cannon 5, Sv Pavao wreck, Mljet, Croatia; 37 – Cannon 6, Sv Pavao wreck, Mljet, Croatia; 38 – Cannon 7, Sv Pavao wreck, Mljet, Croatia; 39 – Cannon 8, Sv Pavao wreck, Mljet, Croatia; 42 – Benin, Nigeria; 43-46 – Cannon A, Megadim wreck site, Israel; 47-50 – Cannon B, Megadim wreck site, Israel; 51-54 – Cannon C, Megadim wreck site, Israel; 55-58 – Chamber 1, Megadim wreck site, Israel; 59 – South North Sea; 60-64 – cannons from Euro-Maasgeul Channel (for details see Electronic Supplement, Sheet 1).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- AAFINALPaperNEWAppendixGunsChemistryNORMALISED.xls