



A unique World War II battlefield artifact fused to a beach deposit

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Abstract

Intensive military operations took place in the southern Baltic Sea during World War II (WWII). It was also a dumping ground for munitions after the war. During storms, military artifacts are washed onto the coast. The Kołobrzeg beach is a place known for such findings. In Kołobrzeg, one of the most recognizable WWII battles between Polish-Soviet and German troops took place. Here, we report on a unique specimen found on the Kołobrzeg beach in 1996. It consists of three fused components, including conglomeratic sandstone, limestone pebble and a fragment of a worn brass gun bullet casing. Heat markings in the form of a dark halo close to the bullet fragment and black efflorescence on the surface of quartz grains suggest that the fusion was caused by heat during the explosion of gunpowder inside the bullet casing. This process led to the formation of a rock-like material resembling a well-cemented conglomerate.

Keywords: sand beach, gun bullet, rock-like material, heating, Kołobrzeg

1. Introduction

Coasts are areas where specific sedimentary formations referred to as beachrocks are formed (Vousdoukas et al., 2007). They consist of different beach sediments, mainly cemented by calcium carbonate. Various artifacts of human origin, such as plastics, slags, fragments of bricks, metal objects and glass, have been found in beachrocks (Fernandino et al., 2020; Gestoso et al., 2019; Santos et al., 2022; Turner et al., 2019; Wang & Hou, 2023). Emery et al. (1954) have reported the occurrence of World War II (WWII) relics such as brass cartridges and shells cemented in the beach sediments of Eniwetok Atoll where military operations took place. Many shells and aerial bombs from WWII were found on Polish beaches near Kołobrzeg, Mielno, Darłówko, Jastarnia and Hel after storms in the 1950s, 1960s and 1970s (Szarejko & Namieśnik, 2009).

Poland is one of the countries that have been most heavily affected by remnants of munitions from WWII, with over 200,000 items located and destroyed each year from 1945 to 1985 (Molski & Pająk, 1985). Multiple accidental findings of ammunition washed out from the Baltic Sea shelf on Polish beaches, including those in Kołobrzeg, were reported over a time span of the 1950s through 1970s (Szarejko & Namieśnik, 2009). However, no specimen composed of a bullet fragment and beach debris has ever been reported.

The military artifact described in this paper is most likely a remnant of the fierce fighting that broke out between Polish-Soviet armed forces and German troops that defended the strategic fortified town of Kołobrzeg from March 4 to 18, 1945 (Baxter, 2025). The Battle of Kolberg was a key part of the East Pomeranian Offensive, aimed at clearing German forces from Pomerania and West Prussia.

Both sides used all types of conventional weapons on land and sea, inflicting heavy casualties running into thousands. According to rough estimates, the Polish-Soviet military units used over 100 guns per 1 km of the front line, and during 10 days of fierce street fighting, about 43 tons of ammunition (approximately 31,500 pieces of bullets) were fired per 1 km² (Zdziech, 2009).

As a consequence, there is a great amount of munitions sunk in the Baltic Sea. Łabuz (2021) reported that in 2007, storm surges of water had washed out ammunition and shell cases from the seabed on the Kołobrzeg beach. Military waste is also washed as a result of shore erosion that occurs on the Baltic Sea coast (Łabuz, 2021). There was only one bigger storm surge (sea level rise ≥ 70 cm from the reference gauge) in Kołobrzeg in 1996, but nine storm surges occurred in 1995 (Wolski & Wiśniewski, 2012). However, it is not possible to link washing up the studied specimen with a specific event.

The aim of this study is to present an explanation for the formation of the unique specimen based on the results of our petrographic and chemical analyses, as well as to discuss its components in the context of local geology and WWII history.

2. Materials and Methods

2.1. The studied specimen

The bullet fragment-bearing specimen described in the present paper was found on 13 May 1996, on the Kołobrzeg beach of the Baltic Sea (northern Poland). Its precise location was the Eastern Kołobrzeg Beach, close to the pier in the splash zone (Fig. 1). It represents a fragment of a brass gun bullet which is rigidly attached to beach debris. To our knowledge, no such specimen has been described in the scientific literature, but pictures of similar specimens can be found on the Internet (e.g., [https://www.thefossilforum.com/topic/91753-storytime-how-did-](https://www.thefossilforum.com/topic/91753-storytime-how-did-this-happen/)

[this-happen/](https://www.thefossilforum.com/topic/91753-storytime-how-did-this-happen/)). Specimens of bullets bound by sand grains and shells have been encountered, for example, on the Pacific shores of the State of Washington (see <https://www.nwnetwork.org/military-and-defense/2020-02-12/they-had-a-beachcombing-blast-on-the-coast-after-old-munitions-washed-ashore>). The latter ones are remnants of military exercises that were carried out in the 1940s, when a naval gunner's school operated in that area.

The specimen was examined under two stereoscopic zoom microscopes: (i) a high-performance Leica M205A (Leica Microsystems, Heerbrugg, Switzerland) with dual coaxial light-emitting diode (LED) illumination, and (ii) a Nikon SMZ 1000 (Nikon Instruments, Tokyo, Japan) with a dual gooseneck flexible arm lamp support and an objective-attached polarized-light illuminator, CL-18. Due to the rare occurrence of such specimens, the authors did not use destructive methods, such as preparing polished thin sections for scanning electron microscopy - energy dispersive X-ray spectroscopy (SEM-EDS) and electron microprobe (EMP) analysis.

2.2. Geological context of the specimen's location

The semi-closed Baltic Sea formed at the end of the ice age within the Baltic Shield and the Precambrian East European Craton. After several glacial episodes, erosion and transport of sediments from cliffs led to the development of sandy beaches up to 35 m in width (Łabuz, 2015; Martewicz et al., 2022). Baltic quartz sands contain 1%–2% of heavy minerals, including garnets, ilmenite, zircon, rutile and leucoxene. Carbonate minerals are scarce (Mikulski et al., 2016). Northwest of Kołobrzeg, small pebble-gravel deposits occur as postglacial remnants (Uścińowicz, 1999). Moraine cliffs and sandy or gravel coasts predominate in the southern Baltic Sea coast (Łabuz, 2015). The moraines in the cliff shores are made up of crystalline rocks, limestone gravels, sandstones and dolomites, and other petrographic types showing the following contribution in the total composition: ~40%–50%, 30%–50%, 10%–



Figure 1. (A) Map of the Baltic Sea with marked Kołobrzeg location. (B) A site on the Kołobrzeg beach where the specimen was found.

15% and 10%, respectively (Seul et al., 2020). There are two sources of beach gravels: erosion of the cliff coast and abrasion of the shallow foreshore.

2.3. X-ray fluorescence (XRF) analysis

Each part of the specimen, i.e., limestone pebble, conglomerate sandstone and gun bullet, was also analyzed for 10 elements (detection limits in mg/kg are given in parentheses): Ba (60), Ca (100), Cu (5), Fe (100), K (100), Mn (30), S (60), Si (40), Ti (50) and Zn (10) using an energy dispersive XRF (ED-XRF) spectrometer, model Thermo Scientific NITON XL3t 960 GOLDD+ (Thermo Scientific, Waltham, MA). This instrument is equipped with an excitation source, a 50 kV X-ray tube with Ag anode (6–50 kV, max 0–200 μ A) and an silicon drift detector (SDD) detector. The time of field portable X-ray fluorescence spectrometer (FPXRF) analysis was 120 s in the AllGeo mode.

The standard reference material (SRM) used for the accuracy of measurements of element contents was NIST 2780—Hard Rock Mine Waste. Quality control included both accuracy (SRM) and precision (triplicate). The average recovery of elements from the SRM was in the range of 80% (Fe) to 110% (Ca), with a mean of 90%. The uncertainty of the method was below 10%. The XRF analysis was performed at the Environmental Analytical Laboratory, Jan Kochanowski University in Kielce.

3. Results and Discussion

The compact specimen of 4.5 cm $\times$ 3.5 cm in size is tripartite. It consists of: (i) a ferruginous micritic limestone pebble, semi-rounded, light brown attached to (ii) a brown to dark brown/black vari-grained ferruginous quartz-limestone sandstone with single limestone pieces up to 10 mm across, and pierced by (iii) a worn brassy $\sim$ 13-caliber bullet. The hole in the bullet fragment suggests that it is part of the bullet case (Fig. 2). All three parts of the specimen are shown in Fig. 3. The bullet fragment lacks any manufacturer's marking, and it is difficult to attribute the bullet to a specific gun. However, based on the size and possible caliber, we speculate that the brass fragment belongs to the bullet used in 13 mm aircraft machine guns, specifically the MG-131 (Rheinmetall-Borsig, Germany), which were used in the Battle of Kołobrzeg.

The limestone pebble is composed of calcite with subordinate silty quartz grains and dispersed iron oxyhydroxides and clay minerals. The most interesting is the central part of this specimen, which is made of detrital quartz and limestone grains bound with

iron oxyhydroxides, clay minerals, and subordinate micritic calcite (Figs. 3C,D; 4). Conglomeratic quartz-limestone sandstone is composed of fine-grained quartz averaging $\sim$ 0.2 mm across with limestone and subordinate sandstone pebbles up to 1 cm in size, cemented with iron (hydro)oxides. Quartz grains are covered with black efflorescence. The gun bullet is surrounded by a black halo of $\sim$ 0.5 mm in size, composed of quartz grains cemented with manganese-iron oxides in some places, forming botryoidal micro-occurrences (Figs. 3A,B). This sintered boundary zone is devoid of clay minerals and micritic calcite. This may suggest heating to a temperature below the melting point of basic detrital specimen ingredients, i.e., quartz grains and limestone particles. However, the temperature was high enough to decompose micritic calcite, and moreover, to recrystallize Fe/Mn oxyhydroxides into their oxide equivalents. In addition, the boundary between a limestone pebble and a conglomeratic sandstone reveals the presence of yellow coloration, which may also indicate heating (Fig. 4).

Brass used in ammunition manufacturing consists of copper 65%–74% and zinc 26%–35% with a trace amount of additives, including Ni, Fe and Pb (Wallace, 2018). However, a different brass composition is also possible with a share of copper from 50% (beta brass in castable) to 95% (gilding metal in ammunition) and zinc from 5% (in different applications, such as coins, cast parts, and ammunition) to 50% (beta brass in castable) (Benvenuto, 2016). The results of chemical analyses support the data obtained from petrographic examinations. Concentrations of major and trace elements within three discriminated parts of the specimen are presented in Table 1. Ferruginous limestone shows the highest concentrations of Ca (36.3 wt.%), Si (2.41 wt.%), Fe (1.24 wt.%) and K (0.364 wt.%). Conglomeratic sandstone contains 14.5 wt.% Si, 14.6 wt.% Ca, 8.37 wt.% Fe, 0.420 wt.% K, showing additionally an enrichment in sulfur (0.804 wt.%) and titanium (0.223 wt.%). Results derived from the XRF analysis of the upper brass part of the examined specimen are probably underestimated because the sample instrument window partly covers an empty space (a hole in the worn bullet case). Because the bullet fragment was exposed to atmospheric conditions, metal contents could have decreased over time due to weathering. There is also a possibility that the lower-cost alloy was used for the production of the bullet cartridge. A shortage of metals during WWII and a need for reduction of production costs may have caused brass in bullet cartridges to be replaced, for example, by steel covered with copper (Petrie et al., 2008).



Figure 2. Major components of a bullet.

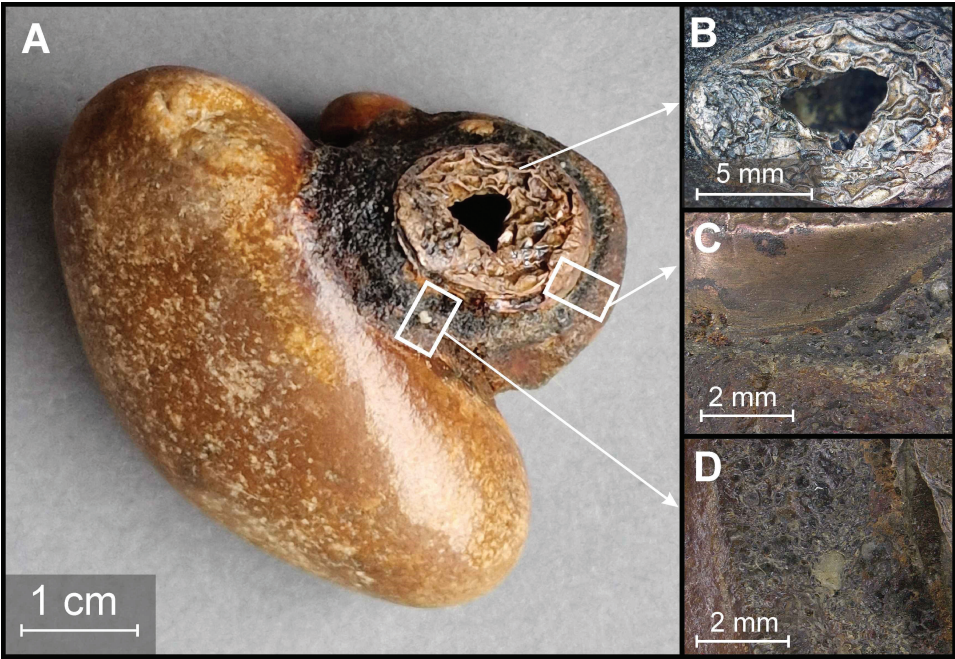


Figure 3. (A) Macro photograph of the worn machine gun bullet embedded in a conglomeratic Fe/Mn-rich quartz-limestone sandstone bound to a semi-rounded micritic limestone pebble (+HCl). Specimen microphotographs: (B) upper part of the worn bullet encircled by a sintered Fe/Mn-rich halo, (C) a fragment of the bullet-sandstone boundary with a distinct Fe/Mn-rich streak, (D) a ferruginous sandstone (center) in direct contact with a limestone pebble (left) and a bullet fragment (right).

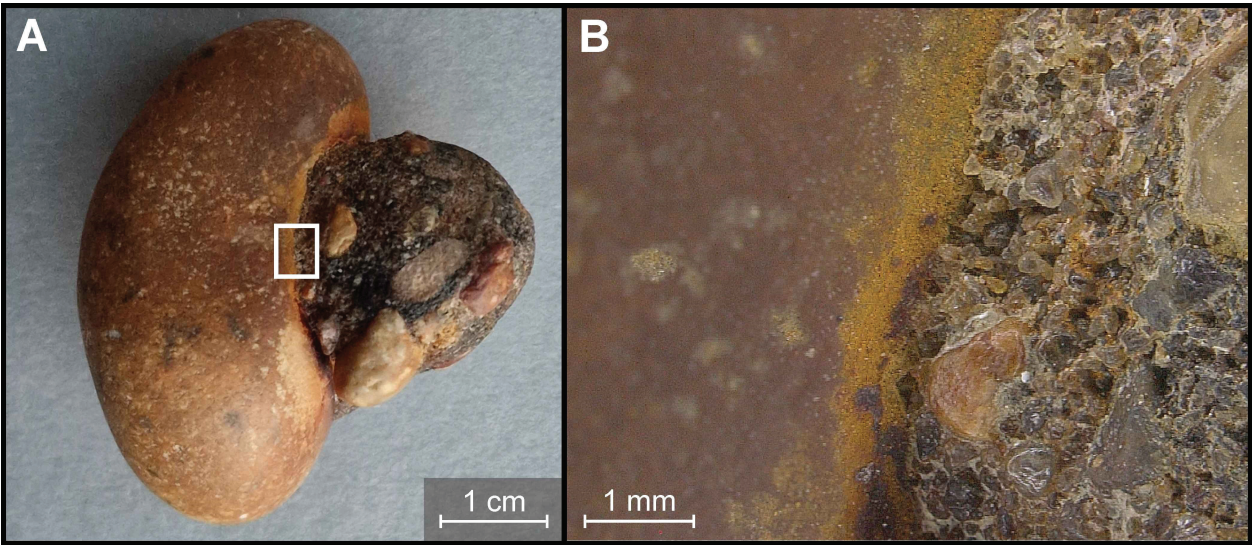


Figure 4. (A) Macro photograph of a ferruginous limestone pebble in direct contact with a conglomeratic sandstone. (B) Microphotograph showing a more detailed microtextural relationship between the conglomeratic sandstone and the limestone pebble; note that the yellow ferruginous streak separates these two petrographic components, which may also point to heating.

Table 1. Concentrations of elements in three different parts of the sample (in mg/kg, otherwise indicated as %).

Part	Ba	Ca	Cu	Fe	K	Mn	S	Si	Ti	Zn
L	320 ± 60	36.3 ± 0.2%	68 ± 14	1.24 ± 0.02%	3642 ± 177	338 ± 56	1217 ± 89	2.41 ± 0.09%	413 ± 81	104 ± 10
S	315 ± 63	14.6 ± 0.1%	90 ± 17	8.37 ± 0.07%	4203 ± 230	1959 ± 112	8041 ± 136	14.5 ± 0.19%	2228 ± 106	112 ± 12
B	380 ± 199	6284 ± 519	67.0 ± 1.6%	2.56 ± 0.03%	405 ± 195	314 ± 97	9970 ± 418	1.70 ± 0.06%	279 ± 65	7.78 ± 02%
CRM NIST 27280 hard rock mine waste										
Certified	993	1950	215.5	2.78%	3.38%	462	1.26%	31%	6990	2570
Determined	973 ± 38	1950 ± 99	177 ± 16	2.22 ± 0.2%	3.31 ± 0.1%	434 ± 58	1.10 ± 0.1%	27 ± 0.1%	6710 ± 102	2082 ± 37
Recovery	98%	100%	82%	80%	98%	94%	85%	86%	96%	81%

Note: L—limestone, S—sandstone, B—brass bullet.

As it has already been mentioned, military artifacts from WWII are often found on the Baltic coast, including beaches in Kołobrzeg (Kobalczyk, 2011). This is the reason why tides and currents brought this specimen to the surface.

The process of the examined specimen formation is unclear and difficult to explain. The temperature of a fired bullet casing for a few seconds after firing is about 60°C (Gashi et al., 2010), whereas the melting temperature of brass is about 920°C (Davies, 1993). The examined specimen shows marks of thermal alteration of a brass fragment (Fig. 3). Thus, an external source of heat should be considered, such as a battlefield fire with high burning temperatures (Kim, 2000).

4. Conclusions

The specimen examined in this study shows features of a rock-like material composed of three distinct parts, namely, a ferruginous micritic light brown limestone pebble rigidly attached to a dark brown ferruginous conglomeratic quartz-limestone sandstone and a worn brassy ~13-caliber bullet. Rocks that were fused with a brass bullet fragment represent gravel typical of beach deposits in this location. This agglomeration of constituents and their characteristic microtextures would not be possible without the impact of a high-temperature process that led to partial melting of the brass alloy and pyrometamorphism of micritic calcite, and recrystallization of Fe/Mn oxyhydroxides into Fe/Mn oxides. Based on the results of this study, it is not possible to conclude whether the whole rocky material had been partly compacted before the bullet impact that changed its matrix, or the originally loosely-bound gravel-sand rock became hardened as a result of these thermally-induced diagenetic processes. This preliminary study may serve as an incentive to search for similar hybrid conglomerates in other areas worldwide.

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Statement of competing interest

The authors declare that they have no known competing interests that could have appeared to influence the work reported in this paper.

References

- Baxter, I. (2025). The east Pomeranian offensive, 1945: Destruction of German forces in Pomerania and West Prussia. *Casemate Publishers*. ISBN 978-1-63624-388-387.
- Benvenuto, M. A. (2016). *Metals and alloys: industrial applications*. Walter de Gruyter GmbH & Co KG.
- Davies, A. C. (1993). *The science and practice of welding* (Vol. 1). Cambridge University Press. ISBN: 9780521435659.
- Emery, K. O., Tracey, J. I. J., & Ladd, H. S. A. (1954). Geology of Bikini and nearby atolls. *U.S. Geological Survey Professional Paper*, 260(260A), 265. <https://doi.org/10.3133/pp260A>
- Fernandino, G., Elliff, C. I., Francischini, H., & Dentzien-Dias, P. (2020). Anthroquinas: First description of plastics and other man-made materials in recently formed coastal sedimentary rocks in the southern hemisphere. *Marine Pollution Bulletin*, 154, 111044. <https://doi.org/10.1016/j.marpolbul.2020.111044>
- Gashi, B., Edwards, M. R., Sermon, P. A., Courtney, L., Harrison, D., & Xu, Y. (2010). Measurement of 9 mm cartridge case external temperatures and its forensic application. *Forensic Science International*, 200(1–3), 21–27. <https://doi.org/10.1016/j.forsciint.2010.03.018>
- Gestoso, I., Cacabelos, E., Ramalhosa, P., & Canning-Clode, J. (2019). Plasticrusts: A new potential threat in the Anthropocene's rocky shores. *Science of the Total Environment*, 687, 413–415. <https://doi.org/10.1016/j.scitotenv.2019.06.123>
- Kim, I. L. (2000). *Battlefield flame/thermal threats or hazards and thermal performance criteria*. Natick Technical Report/TR-00/015L. US Army Soldier and Biological Chemical Command, Soldier Systems Center, Natick, MA
- Kobalczyk, P. (2011). Sappers will examine the beach in Kołobrzeg on Monday (in Polish). *Rzeczpospolita*. <https://www.rp.pl/sluzby/art14657051-saperzy-w-poniedzialek-zbadaja-plaze-w-kolobrzegu>
- Łabuz, T. A. (2015). Environmental impacts—coastal erosion and coastline changes. In The BACC II Author Team (Ed.), *Second assessment of climate change for the Baltic Sea Basin. Regional climate studies* (pp. 381–396). Springer.
- Łabuz, T. A. (2021). Litter sources on the Polish Baltic shore—effect of increased anthropogenic pollution. *Studia Quaternaria*, 38(2), 85–100. <https://doi.org/10.24425/sq.2021.136825>
- Martewicz, J., Kalińska, E., & Weckwerth, P. (2022). What hides in the beach sand? A multiproxy approach and new textural code to recognition of beach evolution on the southern and eastern Baltic Sea coast. *Sedimentary Geology*, 435, 106154. <https://doi.org/10.1016/j.sedgeo.2022.106154>
- Mikulski, S. Z., Kramarska, R., & Zieliński, G. (2016). Rare earth elements pilot studies of the Baltic marine sands enriched in heavy minerals. *Gospodarka Surowcami Mineralnymi*, 32(4), 5–27. <https://doi.org/10.1515/gospo-2016-0036>
- Molski, B. A., & Pająk, J. (1985). Explosive remnants of World War II in Poland. In A. H. Westing (Ed.), *Explosive remnants of war: Mitigating the environmental effects* (pp. 17–32). Taylor & Francis. ISBN 0-85066-303-302.
- Petrie, C. V., Meieran, E. S., Rolph, J. E., & Cork, D. L. (Eds.). (2008). *Ballistic imaging*. National Academies Press.
- Santos, F. A., Rebelo, G., Ferreira, C., Fernandino, G., Giannini, P., Angulo, R., Souza, M., Ferreira, M., & Oliveira, A. (2022). Plastic debris forms: Rock analogues emerging from marine pollution. *Marine Pollution Bulletin*, 182, 114031. <https://doi.org/10.1016/j.marpolbul.2022.114031>
- Seul, C., Bednarek, R., Kozłowski, T., & Maciąg, Ł. (2020). Beach gravels as a potential lithostatistical indicator of

- marine coastal dynamics: The Pogorzelica–Dziwnów (Western Pomerania, Baltic Sea, Poland) case study. *Geosciences*, 10(9), 367. <https://doi.org/10.3390/geosciences10090367>
- Szarejko, A., & Namieśnik, J. (2009). The Baltic Sea as a dumping site of chemical munitions and chemical warfare agents. *Chemical Ecology*, 25(1), 13–26. <https://doi.org/10.1080/02757540802657177>
- Turner, A., Wallerstein, C., Arnold, R., & Webb, D. (2019). Marine pollution from pyroplastics. *Science of the Total Environment*, 694, 133610. <https://doi.org/10.1016/j.scitotenv.2019.133610>
- Uścinowicz, S. (1999). Southern Baltic area during the last deglaciation. *Kwartalnik Geologiczny*, 43(2), 137–148.
- Vousdoukas, M. I., Velegrakis, A. F., & Plomaritis, T. A. (2007). Beachrock occurrence, characteristics, formation mechanisms and impacts. *Earth-Science Reviews*, 85(1–2), 23–46. <https://doi.org/10.1016/j.earscirev.2007.07.002>
- Wallace, J. S. (2018). Chemical analysis of firearms, ammunition, and gunshot residue (2nd ed.). CRC Press. <https://doi.org/10.4324/9781315153254>.
- Wang, L., & Hou, D. (2023). Plastistone: An emerging type of sedimentary rock. *Earth-Science Reviews*, 247, 104620. <https://doi.org/10.1016/j.earscirev.2023.104620>
- Wolski, T., & Wiśniewski, B. (2012). Changes of maximum sea levels at selected gauge stations on the Polish and Swedish Baltic coast. *Studia i Prace WNEiZ*, 29, 209–227.
- Zdziech, M. (2009). Kołobrzaska epopea’45. *Wiedza Obronna (Knowledge of Defence)*, 1, 96–110. (in Polish).

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