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Assessment of the reason for the vitrification of a wall at a hillfort. The example of Broborg in Sweden

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ABSTRACT

It was discovered around 250 years ago that some of the rock material in the walls of some hillforts had been subjected to such high temperature that it had vitrified. This prompted a debate as to the reason for it that is still going on today: did the vitrification come about as a result of hostile action, by accident, or for the purpose of constructing the fort? The present paper is based on the recognition that hillforts are different, and therefore should be evaluated individually. All identifiable factors of interest should be included, and especially those that might disprove any alternative. Thus, incentives, competence and petrographic aspects were evaluated for the hillfort named Broborg (dated to the Migration Period, in Sweden A.D. 400–550), and it is concluded that the vitrification here came about for the purpose of constructing the fort.

1. Introduction

1.1. Some background evidence from britain

The general literature dealing with ancient hillforts and their roles includes the following books: (Harding 1976; Ralston 2006; Brown 2009; Harding 2012; O'Brien and O'Driscoll 2017; Mägi 2015). Vitrified wall material, i.e., rock that has undergone partial melting, appears to have been found only in a small number of all the investigated forts. Calcined rock (carbonate rock that has lost its carbon dioxide) is sometimes included, but this is not dealt with in the present paper.

According to (Nisbet 1974), the first documented observation of vitrification at a hillfort appears to have been made by (Pennant 1776a) during his expedition to Scotland in 1769 when he discovered it at Torr Duin (Tordown). He also discovered it at Finavon (Fine haven) during his second journey in 1772 (Pennant 1776b). It seems that Pennant interpreted the vitrification as of volcanic origin – a theory that was soon to be discarded.

In 1777, the mining engineer John Williams, in a series of letters (Williams 1777), reported about having observed substantial vitrification at several hillforts. He referred to '*the genius and manners of the present Highlanders*' as well as made a comparison with ancient iron beneficiation technology, and concluded that the vitrification had come about for the purpose of constructing the forts.

Ever since, there has been a debate regarding the reason for the vitrification. The early developments are described in (Russell 1894) and the subsequent ones are briefly summarized in the following.

There are three main alternatives: destructive, i.e. a fort was set on

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[1] Until recently.

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fire in order to destroy it; accidental, e.g. a fort caught fire after a strike of lightening; and constructive, i.e. fire was utilized to improve the strength of a fort wall. However, and ever since, the researchers have agreed that essentially all of the examples of vitrification studied have taken place *in situ*.

There is overwhelming evidence, from written sources as well as from excavations, that hillforts were burned quite often, and in some cases even multiple times (MacKie 1976, 205–35; Ralston 2006, 143-63; Brown 2009, 67; Harding 2012, 185-90; O'Brien and O'Driscoll 2017, 408-10). These sources also maintain that such destructive and accidental fires were the most common reason for the vitrification observed. Nonetheless, (Ralston 2006, 143-63; Harding 2012, 188-90) do not exclude the possibility of constructive reasons, and here they explicitly refer to the Broborg hillfort in Sweden - nor were any such possibilities excluded in (Nisbet 1975).

Here follows some examples of the historical dialogue: (M'Hardy 1906) carried out laboratory measurements as well as pilot scale vitrification tests, and concluded that '*it is almost certain that vitrification of the larger masses often met with, if intended as a structural method, must have been a troublesome business*'. Chemical analyses and melting experiments were also carried out by (Brothwell, Bishop and Woolley 1974) who rather considered that the vitrification observed required such '*planning and construction*' that it would be '*a reflection of a cultural tradition, and of the expertise of these people in the use of timber/rock mixes in relation to strong natural draughts*'.

This conclusion was, in turn, repudiated by (MacKie 1976, 206–210) who referred to is as '*creative vitrification*' and found it '*necessary to review again the evidence against that view and in favour of the theory of destruction (deliberate or accidental) of timber-framed walls*'. He considered that '*chemical analyses tell us nothing about how temperature was achieved and even less about the social motives and the activities of the people of the fort*'. He argued that for a vitrification to be classified as '*creative*', it must have taken place before the fort was occupied. He found this nowhere to be the case and emphasized the importance of the approach of *'old fashioned "cultural" archaeologists who dig and study stratification*'. He concluded that '*the evidence that vitrification was caused by the destruction by fire is overwhelming and future workers must face this fact and abandon the fanciful notion that the vitrified rock is the remains of some weird and peculiarly Scottish prehistoric technology*'.

However, Youngblood et al. (1978)[2] and Fredriksson, Youngblood Anthony and Fredriksson (1983) presented evidence for '*creative vitrification'*, by studying material from 11 hillforts. They also determined the FeO/Fe_2O_3 ratio by wet chemical analyses, and found that the vitrification had taken place under chemically reducing conditions (i.e. with carbon monoxide and hydrogen), with temperatures of 900 °C – 1100 °C required for partial melting. They concluded that '*the walls appear to have been built in such a fashion as to withstand, if not be reinforced by, the firing*', and that '*the reducing conditions are evidence for this in that they imply that the walls were compact enough (and probably covered with peat, moss and dirt)*'. The findings were based on extensive chemical and petrographic analyses of the specimens, see e.g. Figures 1 and 2, 3 and 4, and 5 in (Youngblood et al. 1978)[3] showing hand samples, thin sections and wood casts, respectively.

More recently, and in three papers, (Friend et al. 2007, 2008, 2016) report on fusion temperatures for rock containing biotite as low as around 850 °C, thus interpreting that melting might have taken place under uncontrolled conditions, i.e. as a result of hostile action or by accident.

However, (Wadsworth, Heap and Dingwell 2016) found that vitrification may strengthen a wall, and thus '*support a long-since dismissed idea that Iron Age fort walls were intentionally set ablaze in order to fortify the walls*'. Wadsworth et al. (2017)) examined two examples of fort-building materials, granodiorite and sandstone, and developed a model to constrain the sintering behaviour of 45 examples of vitrified walls from Iron Age sites in Europe. It was concluded that the raw building material, i.e., the local rock, governs the efficiency of vitrification for constructive purposes, and that some types of rock were unsuitable for vitrification because the melting temperature is too high. A similar assessment was made earlier by (Nisbet 1975).

Pilot scale experiments have been carried out to assess if hillfort wall vitrification could be the result of hostile or accidental firing of a dry-stone wall reinforced with timber, sometimes referred to as a *murus gallicus*[4]. A summary of these efforts can be found in (Ralston 2006, 156-163). Two tests were carried out by Childe and Thorneycroft (1937), but only the first and larger one is considered here. These authors noted that vitrified walls predominantly came from '*rocks that contain a relatively high proportion of minerals other than quartz*'. Thus, basalt rock was assembled into a stack with dimensions 1.8 m × 1.8 m × 3.6 m and with holes running underneath the construction to create a draft. The arrangement collapsed during the experiment but some vitrified rock material was produced with the largest piece weighing ≈ 180 kg. An even larger test was conducted by Ralston (1986), but for various reasons, only ≈ 3 kg of vitrified rock was produced. Childe and Thorneycroft (1937) and Ralston (1986) found that vitrified rock can be generated by firing a timber laced wall, and that formation of charcoal from the wood must occur before the temperatures required for vitrification can be reached.

2. Approach and objectives

The literature summarised above is consistent with the following quotation from Kresten (2004): '*it is evident that interdisciplinary studies are required in order to solve the problems posed by the vitrified hill-forts*', including archaeological and petrographic investigations. The literature also indicates that different formation conditions apply to different forts. In many cases, the reasons for vitrification are destructive or incidental, and evidence is required to prove that the vitrification in a few cases was for constructive purposes.

Accordingly, this paper focusses on one hillfort, namely the Broborg hillfort in Sweden, and the possible reasons for its vitrification.

The present multidisciplinary approach sets out to examine the questions of (a) incentive, (b) competence, and (c) the architecture and materials properties of the wall itself. There have been two separate excavations at Broborg, one in 1982 and subsequent years, and one in the year 2017. Both were associated with laboratory investigations and literature studies. Work related to the latest excavation is still ongoing. Publications related to the present project include Sjöblom, Ecke and Brännvall (2013), Sjöblom et al. (2016), Weaver et al. (2017), Englund (2018a), Vicenzi et al. (2018), Ahmadzadeh et al. (2020), Plymale et al. (2020), McCloy et al. (2021), Nava-Farias et al. (2021) and Vicenzi et al. (2022).

The purpose of the current Broborg project is twofold: (a) to add to the Swedish heritage, and (b) to support the development of an anthropogenic analogue for the disposal of vitrified nuclear waste. In the latter case, where validated prognoses are to be made on the future behaviour of new materials, it is essential that comparison can be made with similar ones that have been subjected to ageing and weathering under relevant conditions during long periods of time. The Swedish heritage would of course be extended if it might be shown '*that the vitrified rock is the remains of some … prehistoric technology'*, *cf*. the quote from MacKie in Section 1.

[2] Youngblood is the same person as Anthony in the subsequent reference.
[3] Youngblood is the same person as Anthony in the subsequent reference.
[4] *Murus gallicus* was a type of defense wall construction used by the Romans. It consisted of a dry-stone wall reinforced with timber.

3. The Broborg hillfort and its vitrified inner wall

Broborg is located about 20 km east by southeast of Uppsala, Sweden. It is situated on top of an isolated hill rising about 40 m above the surrounding plains and overlooking the river Storån, see Figs. 1 - 2. During the Iron Age and later, Storån was part of a major waterway that connected the powerful Uppsala region with the Baltic Sea. It flowed through the ancient counties Attundaland and Tiundaland, passing Broborg at the border between them.

Since prehistoric times, the landscape has changed substantially, largely due to land-rise associated with the melting of ice after glaciation, together with extensive draining of the land during the 19th century, and this prehistoric route was almost forgotten. Work by Ambrosiani (1961) subsequently unveiled the paramount significance of what he named Långhundraleden [the Långhundra Waterway].

This inspired several local societies within Sveriges Hembygdsförbund [the Swedish Local Heritage Federation] to form Arbetsgruppen Långhundraleden [the Working Group the Långhundra Waterway] to research the prehistory and history concerning the waterway and to document it in two comprehensive books (Arbetsgruppen Långhundraleden 1993, Arbetsgruppen Långhundraleden 2011). The group then inspired Upplandsmuseet [the Uppsala County Museum] to conduct an excavation at Broborg during 1982–1983 and some subsequent years. The results are documented in the books by Arbetsgruppen Långhundraleden, and by Fagerlund (2009). Details on the vitrification are published in (Kresten and Ambrosiani 1992, Kresten and Kero 1992, Kresten, Kero and Chyssler 1993, Kresten 2004).

The second excavation came about after it had been discovered that the hillfort glass might serve as an anthropogenic analogue to nuclear waste glass (Sjöblom, Ecke and Brännvall 2013), and an early plan for this work can be found in (Sjöblom et al. 2016). The excavation took place in 2017 (Englund, 2018a; Englund, 2018b), and further publications emanating from the project presently include (Sjöblom, Ecke and Brännvall 2013, Sjöblom et al. 2016, Weaver et al. 2017, Vicenzi et al. 2018, Plymale et al. 2020, Ahmadzadeh et al. 2020, Nava-Farias et al. 2021, McCloy et al. 2021, Vicenzi et al. 2022).

The inner wall (see Figs. 1 – 5) has a circumference of around 200 m, and 1 m sections of the wall at different locations were examined in each of the excavations.

Around 150 m of the inner wall are vitrified to an approximate depth of 0.5 m and to a width of around 1 m and up to 1.5 m, as was determined by examination of the wall after the topsoil had been removed (Löfstrand 1982), and supplemented with the use of magnetometry (Kresten and Kero 1992, Kresten, Kero and Chyssler 1993). The depth of vitrification varies, with 0.3 m reported in Kresten and Ambrosiani (1992), 0.7 m reported in Kresten, Kero and Chyssler (1993), with a depth of 0.2 m at the edges and 0.8 m in the middle reported in the second excavation.

After the topsoil overlying the vitrified wall was removed during the first excavation, it could be seen that the surface is quite flat and that the wall consists of a series of 'boxlike' structures, $\gtrsim 1$ m in length (Kresten, Kero and Chyssler 1993).

The age of the fort has been evaluated as follows. During the first excavation, a piece of charcoal was removed from a hole, ~0.5 m in depth and just inside the inner wall, with evidence suggesting that it used to hold a wooden pole. Carbon-14 (C14 or ^{14}C) analyses of the charcoal piece, sample St 8675), indicated a time period of A.D. 430 – 660 (1 sigma) and 340 – 780 (2 sigma), (Fagerlund 2009).

During the second excavation, it was observed (Englund, 2018a; Englund, 2018b) that some fines, likely from the deterioration over time of some fire-cracked material, had formed a layer on top of the wall as well as on the adjacent ground. It was superimposed in part by a settlement layer from activities inside the fort. This cultural layer could be dated to the period A.D. 432 – 542 (1 sigma) using the C14 method. The

Fig. 1. The hillfort Broborg with the river Storån in the background. Traces of the meander and associated ancient ford are also visible. The present straight course of the river is a result of drainage operations in the 19th century. The photograph was taken by Jan Norrman in the year 1991. It was made available by Riksantikvarieämbetet (The Swedish National Heritage Board).

Fig. 2. The hillfort Broborg together with the river Storån and the Vallby Ridge as well as the remains of the meander and the associated ford. The river got its straight course during drainage operations in the 19th century. Copyright Lantmäteriet (the Swedish mapping, cadastral and land registration authority).

figures are a result of a combination dating based on samples Ua-57543, Ua-57545 and Ua-57546 with A.D. 420–590, 410 – 560 and 420 – 580 (2 sigma), respectively. Thus, the vitrified part of the fort appears to be somewhat older and likely from around the beginning of the 5th century (Englund, 2018a; Englund, 2018b).

The vitrified part of the wall has also been subject to archaeomagnetic dating (Ahmadzadeh et al. 2020) which indicates three possible time intervals: A.D. 389 – 579, A.D. 602 – 752, and A.D. 965 – 1300 (2 sigma). Of these, A.D. 389 – 579 is in a good agreement with the C14 measurement of A.D. 432–542 for the cultural layer (Englund, 2018a; Englund, 2018b).

Studies of vitrified parts of the wall are presented primarily in Kresten and Ambrosiani (1992), Kresten and Kero (1992), Kresten, Kero and Chyssler (1993), and Kresten (2004) as well as in Nava-Farias et al. (2021), McCloy et al. (2021) and Vicenzi et al (2022).

Kresten and Kero (1992) and Kresten, Kero and Chyssler (1993) carried out detailed measurements to determine that the raw material for the vitrified wall contained 30 % amphibolite (diabase/dolerite) and 70 % gneissic granite. This ratio is approximately ten times higher than the amphibolite-to-granite ratio in the background material collected from an area more than 250 m away from the fort, with natural variation insufficient to explain the predominance of amphibolite in the vitrified parts of the wall. The melted material is shown in Figs. 6 – 7, see also Fig. 4. The amphibolite melted to a greater degree than the granite, with the melting process producing vesicles such that the partially melted rock expanded and filled the space between the gneissic granite pieces, thus chemically merging and bonding the various pieces of rock together.

The gneissic granite melted to a lesser extent, producing a melt with a much higher viscosity (McCloy et al. 2021). Thus, two glasses were formed, a silica-rich light glass, largely from the gneissic granite, and a dark glass, with a lower silica content, from the amphibolite.

Most of the gneissic granite material in the wall did not melt upon exposure to the high temperatures, but instead became fire-cracked and mechanically weakened. Despite this, the vitrification of the 'boxlike' structures substantially strengthened the wall, and the vitrified part could be broken only by sledgehammers.

4. The reason for the vitrification

4.1. Incentives

The hypothesis that the vitrification was intentional and for the purpose of construction should be discarded unless it can be reasonably argued that the ancient people had a clear incentive to spend considerable effort on strengthening the fortification.

It was mentioned in Section 3 that Långhundraleden was a major waterway connecting the mighty Uppsala region with the Baltic Sea, and that the hillfort Broborg was located right at the border between two ancient counties. Moreover, it was overlooking a ford and an associated ancient road, see Figs. 1 - 2. It is also well known that, at the time the fort was constructed, Sweden was divided into various chieftains (Gahrn 1988; Iversen 2019). Reasonably, the fort had a control function in peace time, and a defence function whenever the chieftains were at war. Thus, this site warranted heavy investment, in comparison to the vast majority of other hillforts in central Sweden.

Fig. 3. A part of the inner wall at Broborg at the beginning of the excavation in October 2017. The picture shows the vitrified part and its even upper surface as well as some empty space underneath. Photographer Rolf Sjöblom.

There are several incentives to invest resources in making a vitrified wall at Broborg. Firstly, the rocks available to build the fort had become rounded by the action of ice during glaciation and were susceptible to movement because of the freezing and thawing of the land beneath, thus, vitrification of the rocks to prevent them from moving was likely essential for the stability of the wall. Secondly, if timber was used to form the base of the construction, it would be susceptible to rot, thus, constructing the base out of vitrified rock would alleviate challenges associated with replacing timbers at the bottom of the structure. Thirdly, if the base of the fort was constructed out of timber, it would be susceptible to intentional or unintentional destruction by fire, whereas the vitrified material would provide a fire-resistant base.

4.2. Competence

A possible reason for discounting the constructive vitrification hypothesis would be if it might be assessed as likely that the ancient people lacked the knowledge and skill required to generate a suitable method for hillfort vitrification. Wall vitrification is difficult and complex, and requires some ingenuity, as well as a significant amount of development work, as demonstrated by the various pilot scale experiments conducted. However, the people at the time were able to produce high temperature ceramics, tar, charcoal and iron, and it should be considered if elements of such technologies could have been transferred to wall vitrification. To be regarded as relevant, such capabilities must have existed in the part of Sweden in question at the time of the vitrification.

Iron beneficiation has been practiced in the Uppsala region in Sweden since the Later Bronze Age (1100 – 500BCE) (Hjärthner-Holdar 1993), i.e., a thousand years or more before the vitrification at Broborg took place, cf. Section 3. The temperature in the charcoal in a bloomery furnace has been determined to be around 1200 °C, see (Portillo-Blanco et al. 2020) and references therein. It is a prerequisite for the operation that the hearth be enclosed (except upwards from where the feed was added) in a furnace made from material able to withstand this temperature.

Similar requirements to withstand high temperatures apply to the use of ceramics for casting of metals; their elemental and phase compositions being quite different from those in ordinary pottery. Such ancient high temperature ceramics are referred to in modern technology as '*refractory ceramics*'. Several prerequisites apply for a raw material to be used for such purposes, including modifications of the compositions by mixing raw materials and by adding various tempers (Forenius et al. 2014; Eriksson, 2009; Phelps and Wachtman, 1986). One common temper used was asbestos which is a fibrous amphibole (Eriksson 2009). Diabase / dolerite rocks (the type of rock vitrified at Broborg) were also used for this purpose (Brorsson and Ytterberg 2018).

A bloomery furnace is a shaft type of furnace which, for the most part, was fired with charcoal, thus allowing for a high temperature to be reached such that firstly, the iron oxide was reduced to iron metal, and secondly, that the slag melted and could be separated from the soft metallic iron (that could be wrought). In Sweden, bellows were used for the most part in order to achieve a sufficiently intense fire with the high temperature required.

This contrasts with the roasting of the iron ore (mostly in the form of hydrate, e.g. limonite, lake ore, bog ore, and red earth) which took place under likely oxidizing conditions with layers of horizontal logs with ore between them. This might have been somewhat similar to a fire in a '*murus gallicus*', but with the difference that the cross sections of the logs used was probably much smaller (Englund 2002), i.e. among the smallest used for pulpwood today. The temperature is much lower than in a Bloomery furnace but sufficiently high to drive off the bound water and to make the ore porous such that, in the Bloomery furnace, carbon

Fig. 4. The cross section of the inner wall at Broborg. Profile to the east as in Fig. 5a. The photograph was taken by Rolf Sjöblom during the excavation in October 2017. The markers represent sampling points for the pulverized fire-cracked rock material.

monoxide might enter the interior of the grains by means of diffusion and convert the iron oxide to metallic iron (i. e. through firing under reducing conditions).

It has been shown (Ölund 2007, 643)[5] that charcoal has been produced in Sweden since the Early Iron Age (500BCE – A.D. 400) and likely as early as the Later Bronze Age (1100 – 500BCE). The conversion of wood to charcoal was carried out in pits covered with turf, slowly, at a low temperature and with a minimal access of air in order not to burn more of the material than necessary.

A related arrangement was used for the beneficiation of tar. Here the flow of air was directed such that the charcoal was combusted and the volatiles were beneficiated. Consequently, the ash content in charcoal from tar beneficiation is much higher than that from ordinary charcoal. Pits for tar beneficiation date back to the Roman Iron Age (A.D. 0 – 400) (Svensson, 2007; Hennius, 2018), see also (Hennius 2005; Hennius 2007).

In summary, the people, at the time of the vitrification at Broborg, had the skill and competence needed to carry out high temperature operations, under oxidizing as well as reducing conditions.

4.3. *The vitrified wall at Broborg and its genesis*

It was mentioned in the discussions on the pilot tests (cf. Section 3) that it is necessary for wood to be turned to charcoal before a sufficiently high temperature might be reached such that the rock would melt partially. This question has been analysed further from a combustion technology perspective (Sjöblom, Ecke and Brännvall 2013), and it was found that it is not actually the total thermal energy that matters, but the calories available at the temperatures required to melt the rock. Contrary to charcoal, combustion of wood requires that many calories are spent on vaporizing water, thus leaving fewer calories to add to the temperature for melting. This includes the water vapor formed when the hydrogen and oxygen atoms chemically bonded in the wood are forming water during combustion. Further calories are "lost" because of the carbon monoxide – dioxide equilibrium, which implies that, at the highest temperatures, and in equilibrium with carbon in the charcoal, essentially only carbon monoxide is formed (Hägg 1966, p 592, section 23-2f).

When considering the architecture of the wall itself, the first question to be considered is whether or not the vitrification at Broborg was intentional. If it were not intentional, then one would certainly expect the fuel to be wood, and the mix of stone material reflecting that found naturally in the surrounding area. The firing cannot have been unintentional for the following reasons:

a. The conditions for any efficient generation of charcoal and that of melting the stone material are very different. In an efficient process, charcoal would be produced slowly, at a low temperature and with a low flow rate for the air, while the opposite would be the case at the highest temperatures. Encasement would be needed in both cases to ensure reducing conditions at the low temperature in order to avoid burning more charcoal than necessary, and to allow a strong draft at the high temperature to give rise to an efficient and intensive combustion. Such conditions can rarely be met in the absence of human intervention.

[5] The Swedish letter Ö is to be found at the end of the alkphabet.

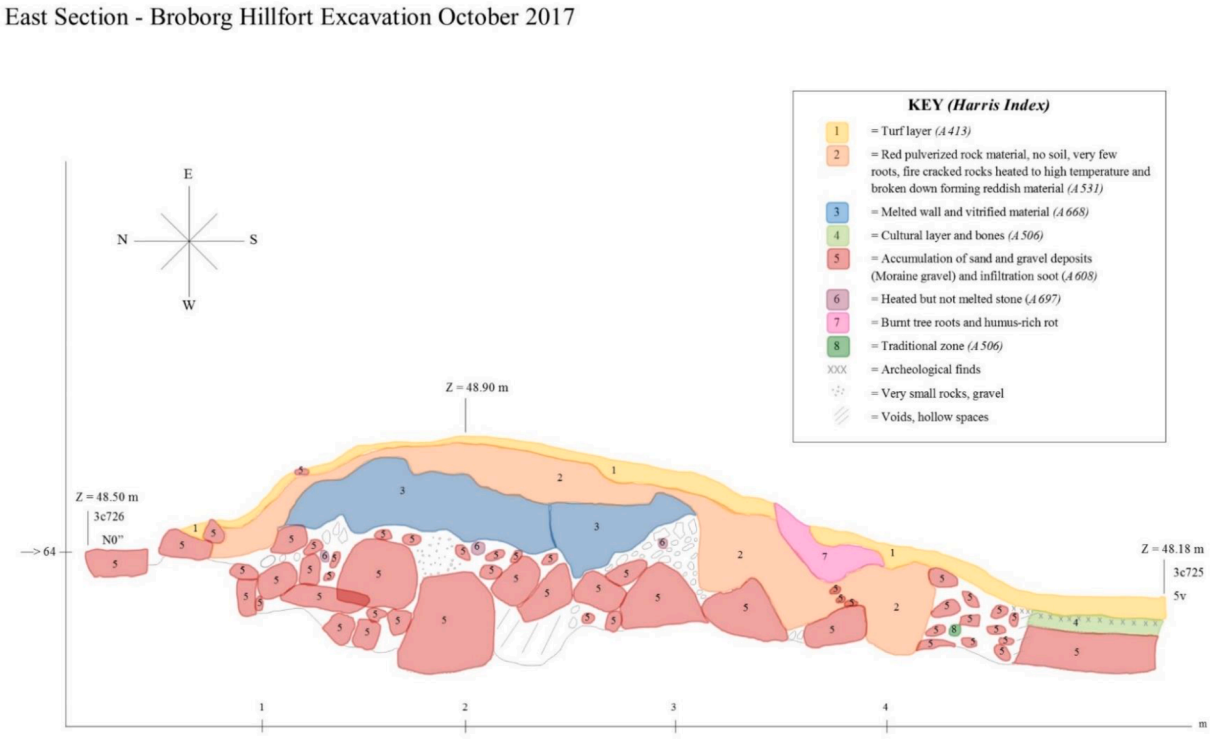

Fig. 5a. Drawing of the cross section of the inner wall at Broborg. Profile to the east. Areas labelled no 5 also contained cobble and boulder size material, cf. Fig. 4. The excavation was carried out in October 2017. This figure is very similar to Figure 9 in (Englund 2018a, Englund 2018b) in which also further information on the excavation can be found.

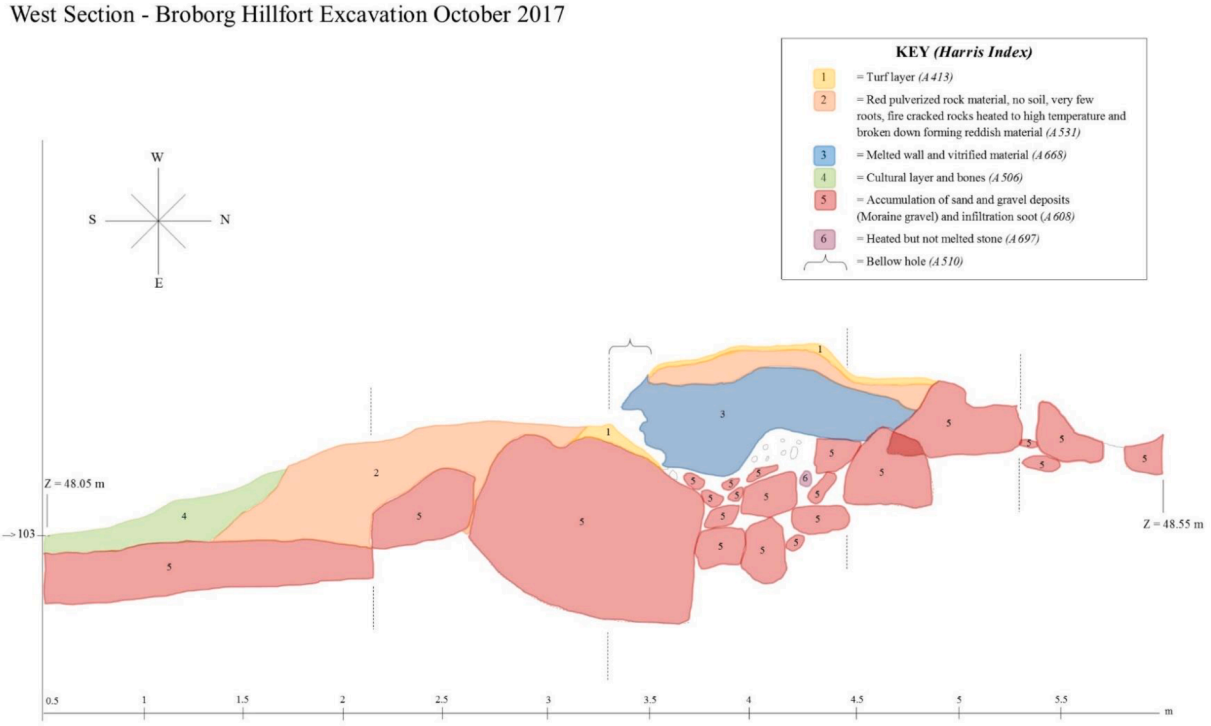

Fig. 5b. Drawing of the cross section of the inner wall at Broborg. Profile to the west. Areas labelled no 5 also contained cobble and boulder size material, cf. Fig. 4. The excavation was carried out in October 2017. This figure is very similar to Figure 10 in (Englund 2018a, Englund 2018b) in which also further information on the excavation can be found.

b. There would have been no enrichment of amphibolite; such enrichment is required to fuse together several pieces of rock to form the large sintered entities that are observed at Broborg.

c. Any unintentional amphibolite enrichment would not have been optimized for contact between the pieces of gneissic granite, and it is this contact that is required to minimize the risk of collapse.

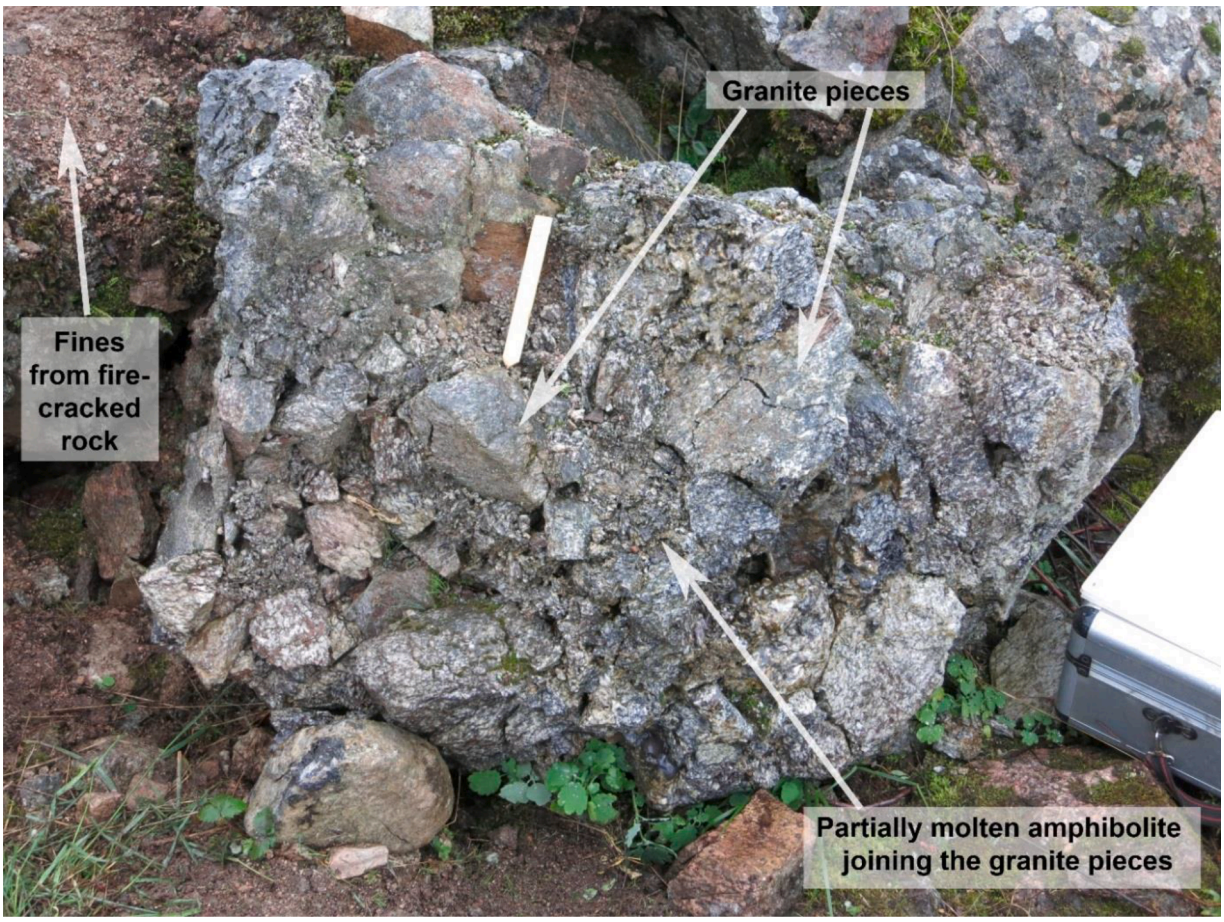

Fig. 6. The underside of a block of vitrified rock material from the excavation in 1982 and some subsequent years. Pieces of granite rock are joined together by partially molten diabase/diorite/amphibolite. The marker is 15 cm long. Picture taken by Rolf Sjöblom in October 2017.

d. The amphibolite would not have been hewn; most pieces of rock at the site have a rounded morphology as a result of the action of ice during glaciation, but the amphibolite was observed to have sharp cut edges.
e. There would not have been cultural layers representative of human occupation on top of residues from the vitrification of the wall.
f. The box-like constructions would not have been arranged to form a 150 m circumference if they were the result of an unintentional fire.
g. The imprints of charcoal would not have had straight terminations, indicating that the charcoal had been prepared in advance.

On these grounds, it is assessed that the vitrification at Broborg was intentional.

Now to the question of whether it took place as a result of a hostile action. For this case, the initial wall would not have been vitrified when it was made, but vitrification would have taken place later as a result of hostile action.

This is discounted by the evidence of human occupation after the vitrification. It is also unlikely that an enemy would arrange the vitrification such that it formed a 150 m of flat surface with a good capacity to carry loads, and instead one would expect an uneven surface. Indeed, all of the observations presented, cf. items (a)-(g) above, either support, or are indifferent to, the hypothesis that the vitrification was intentional and for the purpose of construction.

4.4. Conclusion on the reason for the vitrification

In conclusion, this analysis indicates that there existed, during the Migration Period, i.e. A.D. 400 – 550, a technology in the Uppsala region by means of which strong and durable vitrified walls could be constructed.

It should be noted that the present conclusions apply only to Broborg. The various prerequisites may be very different elsewhere. It is hoped, though, that the present approach might help with the interpretation of the genesis of other hillforts.

5. Questions that have not been (fully) resolved

5.1. Rationale

Notwithstanding the conclusion regarding the reason for the vitrification, there are still some questions that remain. It is appropriate when such conclusions as those above are presented, that also lack of knowledge be declared, thus facilitating any comprehensive and conscientious analysis and review by any reader.

5.2. The area under the vitrification

The vitrified parts of the wall rest on large stones with spaces in between them and openings to the exterior of the wall, possibly serving the purpose of supplying air for the combustion, see Figs. 3 - 5. A plausible arrangement for the firing might have been a stack of gneissic granite cobbles interspersed with small pieces of amphibolite and charcoal material on top of the larger stones together with supply of charcoal or wood underneath the stack. Likely, pre-heating was required before the charcoal in the bed to be vitrified would catch fire. Similarly, and in view of the heat capacity of the rock material, it might be expected that very little charcoal would remain afterwards. At least, this is

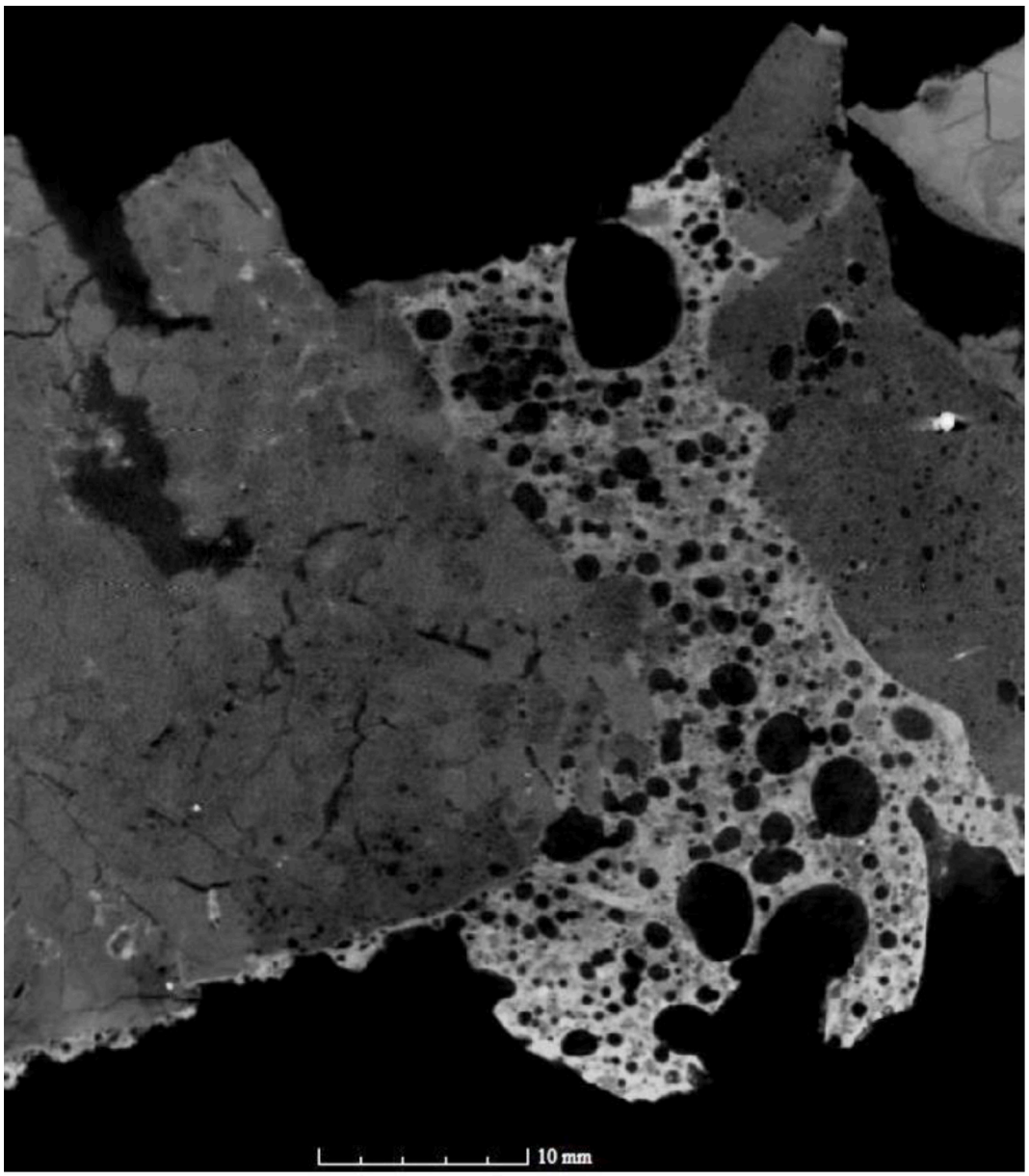

Fig. 7. X-ray tomography image of vitrified material from the excavation at Broborg in 1982 and some subsequent years. Light colour refers to high density, and dark to low. Image recorded at Pacific Northwest National Laboratory, see the Appendix in (Sjöblom et al. 2016) for further detail.

what has been observed.

In view of this scenario, it is warranted to ask if the draft-holes and the areas underneath might not have provided opportunities for an enemy to put the fort on fire. After all, it was concluded above that the vitrification forms an even layer suitable for carrying a stone wall reinforced with horizontal timbers on top.

This is assessed not to be the case, however, since the vitrification forms a tight layer with a high heat capacity, thus making any such ignition of timber on top difficult.

5.3. The superstructure on top of the vitrification

The vitrification forms an even surface suitable for carrying an appreciable load such as a dry-stone wall. There is presently no stone on top of the vitrified part, but plenty of well-rounded stones outside of it scattered on the steep slope below. The present authors offer no explanation as to why there are practically no stones on the inside. It is conceivable, that some of these stones may once have formed a timber reinforced dry-stone wall on top, just as is suggested in many papers on hillforts, thus forming a *murus gallicus*, possibly in combination with a palisade. No pole holes have been found to support this, but on the other hand, it is possible to make such a stone structure using only horizontal timbers. Many of the stones may well have formed an obstacle as they lie in the form of a *'chevaux-de-frise'* as described in (Harding 2012, 190-192).

5.4. The combustion and vitrification processes

It was found that vitrification had taken place under reducing conditions (Youngblood et al. 1978) and that this has been interpreted (Childe and Thorneycroft 1937; Ralston 1986) to mean that it was necessary to maintain a reducing atmosphere, at least during part of a vitrification process, in order for the timber to first turn to charcoal and then burn at a very high heat. It was assessed that this necessitates some kind of encasement, e.g., by means of covering with turf.

A similar, but yet somewhat different experience is mentioned in

(Kresten and Kero 1992) who determined that amphibolite from Broborg melts (solidus) at 1076 °C in nitrogen and at 1165 °C in air. It appears from the text that vitrified rock from Broborg melts at 1017 – 1078 °C, and thus at temperatures not far from the one for nitrogen. That there may be such a difference is, at least in part, corroborated in (McCloy et al. 2021).

Experiments were conducted by Kresten and Kero (1992) to determine the reason for the difference in melting points. First, it was attempted to heat amphibolite over charcoal using a forced draft and with an excess of air, and this resulted only in fire-cracking of the rock. However, when a cover of turf was applied, melting was observed. This was interpreted (Kresten and Kero 1992) to be a result of the influence of the steam formed.

It may be tempting to draw such a conclusion since water has an extremely strong influence on geochemical reactions at some depth in the crust. However, this is not the case at ambient pressure, and, for instance, presence of water in a solid fuel does not (with some exceptions) have any major influence on ash formation during combustion and incineration.

Moreover, (Kresten and Kero 1992) used charcoal, wherefore they would not have needed any encasement in order to char any wood to become charcoal.

Consequently, the reason for the difference in solidus melting temperature ought to be sought elsewhere. It is well known in the chemical literature that the fusion characteristics, as well as the viscosity of a melt, may be highly dependent on the oxidation state of the elements involved. Iron in a melt of metal oxides may act as a network former when appearing as iron-III, and as a network modifier when as iron-II (Dingwell and Virgo, 1987). This means that the fusion temperature as well as the viscosity of the melt is lower for iron-II as compared to iron-III, see also (Stabile et al. 2021; McCloy et al. 2021).

This is highly significant in conjunction with combustion of coal, in which case reducing conditions may give rise to fusion temperatures 50 °C – 200 °C lower as compared to oxidizing conditions, and for iron contents higher than 5 % figured as iron-III-oxide (Huffman, Huggins and Dunmyre 1981). In fact, this is one of the major reasons why coal firing plants have changed to processes by means of which the coal particles are fully oxidized before they hit any surfaces where they might otherwise cause formation of scale (Raask 1985, 5-7). It might be added that the amphibolite / dolerite / diabase at Broborg contains about 10 % – 11 % of iron figured as iron-II-oxide (McCloy et al. 2021).

The above does not necessarily imply that iron became reduced to mostly iron-II in any particular pre-historic hillfort vitrification process. For instance, it may be necessary for there to be an open pore structure that allows the surrounding carbon monoxide and hydrogen to reach the interior of the pieces of rock and cause the partial reduction of iron. In the case of iron hydroxide type of ore, this was mostly assured by means of roasting the ore before it underwent reduction (Englund 2002, Overman 1852, Overman 1854).

It can thus be hypothesized that details of a vitrification process, and, in particular, the redox (oxidation–reduction) conditions, might have a major impact on the prerequisites for as well as the result of any vitrification. However, this does not appear to have been investigated.

Nonetheless, it is assessed here, that this question does not alter the conclusion above regarding the reason for the vitrification at Broborg.

It might be added that in a sample of rock consisting of metallic elements in oxide and hydroxide forms, the mineral composition depends not only on the relative amounts of the constituent metallic elements, but also on the content of bound water and the redox conditions. This is studied extensively in petrology and vulcanology, see e. g. (Frost and Frost 2019) for a general overview, as well as (Ren et al. 2006) for reducing conditions at low pressure, and (Anthony and Titley, 1988) for oxidizing conditions.

6. Main conclusions

The reason for the vitrification at the hillfort Broborg near Uppsala in Sweden were analysed from the perspectives of incentive, competence and the evidence from the wall itself, and it was concluded that there existed in the region, at around the 5th century CE, a technology by means of which strong and durable vitrified walls could be constructed. This finding not only extends the Swedish cultural heritage, but also facilitates the use of the wall material as an anthropogenic analogue in studies of the long-term properties of nuclear waste glass. The analyses include unresolved questions, none of which is found to warrant any alteration of the main conclusion.

7. Disclaimer

Trade names and commercial products are identified in this paper to specify the experimental procedures in adequate detail. This identification does not imply recommendation or endorsement by the authors or by the National Institute of Standards and Technology, nor does it imply that the products identified are necessarily the best available for the purpose.

Author contributions

This is a multidisciplinary project and all authors have contributed based on their respective areas of expertise. A first draft was prepared by Rolf Sjöblom, Carolyn Pearce, Jamie Weaver, Eva Hjärthner-Holdar and Erik Ogenhall, and all authors have participated in the further development of the manuscript.

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

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