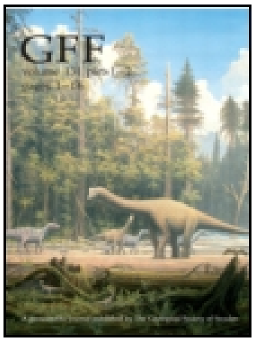

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Geology of the vitrified hill-fort Broborg in Uppland, Sweden

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Broborg is a hill-fort from the Migration Period, situated about 20 km southeast of Uppsala. Vitrification is found around almost the whole circumference of the inner rampart, with the notable exception of the entrance. Vitrification occurs along the inner face, forming a 100–150 cm wide, 40–70 cm deep layer consisting of amphibolite melt, penetrating and cementing blocks of gneissic granite. Amphibolite has been selectively enriched only in the vitrified parts. Temperature required for vitrification is about 1130°C, with low oxygen fugacities. Charcoal, rather than wood, is the most plausible fuel that has been used. Box-like structures, about two metres long, suggest vitrification in sections. All evidences indicate a constructive formation of the vitrified wall, employing forced draught (= bellows) to a confined space. Melting temperatures for vitrified products from several European forts are given. ☐ *Vitrification, hill-fort, geology, melting, Broborg, Sweden, Europe.*

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Vitrified forts are prehistoric fortifications where the building stones of the ramparts are bound together by a vitreous material, produced in situ by the action of heat (similar to the definition by Christison 1898, p. 169). About 130 vitrified forts are known to occur in Europe. Most of them are found in Scotland (82 confirmed occurrences), France, Germany, and Czechoslovakia. A small number are found in Ireland, Wales, England, and on the Isle of Man. Ever since the first description of the phenomenon some 220 years ago (Pennant 1771; West 1777), research on vitrified forts have engaged scholars and scientists.

Disregarding more exotic theories, two main lines of explanation for the phenomenon of vitrification have been suggested. Vitrification has been suggested as a constructive method used by the Scots (or: Celts) instead of mortar. Other investigators advocated a destructive principle: vitrification resulted from the firing of timber-laced ramparts by enemies. For a period of about 150 years, both theories found their supporters, possibly with some advantage for the constructive ideas. Since Childe & Thorneycroft (1973*b*) produced vitrified material when burning a timber-laced rampart, the destruction model gained space and is now advocated by most archaeologists (see Nisbet 1982; Ralston 1986). Scientists, however, still consider certain constructive aspects in vitrified forts (Brothwell et al. 1974; Youngblood et al. 1978; Fredriksson et al. 1983).

Phneomena related to vitrified forts have been called 'calcined forts', in which the construction material was limestone, which was burnt. In Sweden, Torsburgen on Gotland is a good example (Engström 1984). Also known are walls which have been burnt down without producing vitrification, e.g., at Clatchard Craig, Scotland (Close-Brooks 1986). These examples are not discussed in the present study.

The first reference to a Swedish vitrified fort is by Erdmann (1868), regarding Broborg. The first publication covering most vitrified forts in Sweden appeared only recently (Kresten & Ambrosiani 1992). Since then, a few additional occurrences have become known. Among the 13 Swedish forts (Fig. 1), only three — Broborg, Kollerborg, and Norsborg — are identified as vitrified forts *sensu stricto*. At all other sites, vitrified material occurs as sporadic finds or is not obviously connected with the rampart itself (see definition above). None of the vitrified walls of the three vitrified forts have been excavated properly. The best exposed and investigated site is Broborg, which is the main issue of this study.

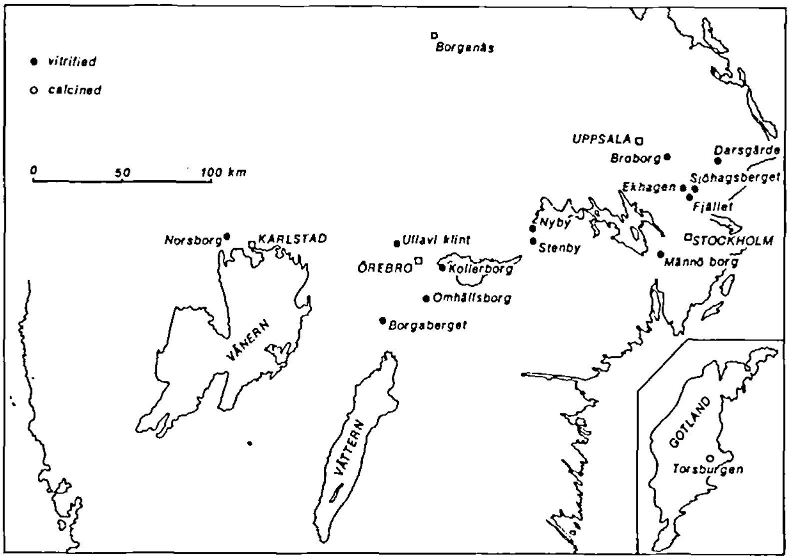

Fig. 1. Sites with vitrified material in Sweden. Vitrified forts *sensu stricto* are Broborg, Kollerborg, and Norsborg. Other sites contain occasional vitrified material. Torsburgen is calcined (= burnt lime). Borganäs, in Borlänge, is a medieval fortress where molten bricks are found.

Broborg

Broborg (17°37'33"E, 59°54'08"N) is situated some 20 km southeast of Uppsala, on the top of a moraine hill overlooking and controlling the "Långhundraleden" (Ambrosiani 1961), a waterway navigable until about 400–500 A.D. The fort is halfmoon-shaped, with a complete inner rampart and a crescent-shaped outer rampart towards the southeast (Fig. 2), where also the entrance is. Both ramparts are dry-stone walls (Figs. 3, 4), constructed using boulders from the glacial drift. Socket-beams or other timber constructions are apparently lacking. The remaining parts of the dry-stone wall (Fig. 2) are all about 2 m high, with an estimated thickness olf 4–6 m.

About 5 m outside the dry-stone wall at the north of Broborg (*e* in Fig. 2), a large glacial boulder was discovered by one of us (L.K.), carrying a hewn hole and groove (Fig. 5). The hole has, in section,

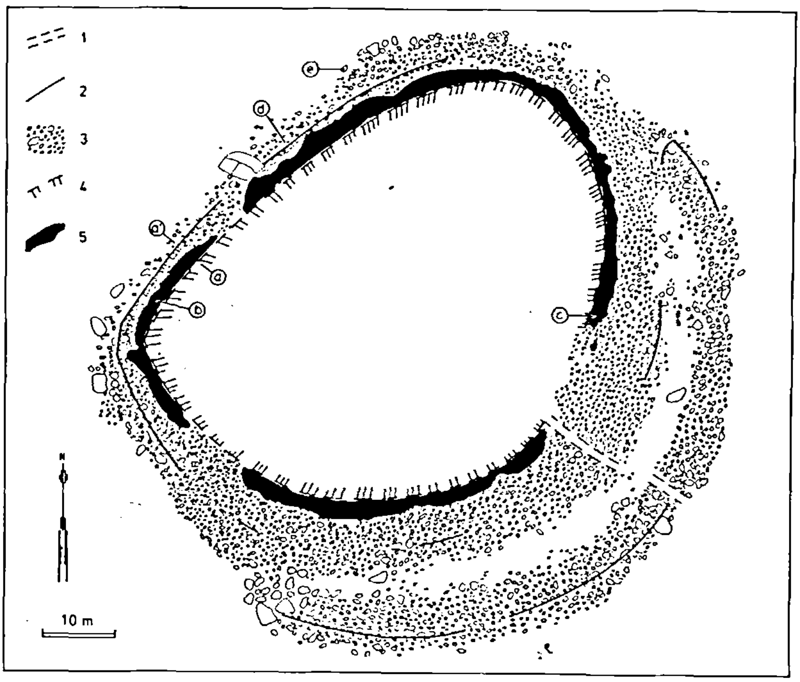

Fig. 2. Plan of Broborg hill-fort. 1 = entrance, 2 = standing dry-stone walls, 3 = collapsed parts of the ramparts (smaller boulders only schematic), 4 = inner face of rampart, 5 = vitrified material. Boulders inside the fort are not shown.

Fig. 3. Outer rampart of Broborg, southern side. Dry-stone wall constructed using boulders from the glacial drift. Scale is one metre.

Fig. 4. Inner rampart of Broborg, northwest side (*d*, Fig. 2). Dry-stone wall, no signs of socket-beams. Scale is one metre.

the form of an equilateral triangle (base is 21 mm). It is about 65 mm deep. The groove is 125 mm long and between 19 and 21 mm wide, straight, striking 127.5°. It is tentatively explained as having formed the base of an instrument aimed at the setting sun at Beltane day, the beginning of summer according to the Celtic calendar, about 500 A.D. (G. Henriksson, pers. comm.).

Mejdahl (1983) gives a TL date of 740 ± 100 A.D. for "burnt stones just underneath the vitrified layer" (sample taken at *b* in Fig. 1). A "posthole inside the rampart" gave a ^{14}C age of 446 A.D. (Löfstrand 1983), which agrees with the find of a glass bead inside the fort belonging to the period 400—575 A.D. (Löfstrand 1983).

Fig. 5. Hewn hole and groove just north of Broborg (*e*, Fig. 2), with possible astronomical implications (see text).

The building material

The principal rock types in the glacial drift are gneissic granite and amphibolite. Other rock types — metasediments and metavolcanics — constitute only 3.4 % of all boulders counted. For simplicity, the term 'boulder' used here includes both cobble and boulder according to Wentworth's scale. The result of one boulder count (totally 1972 boulders) is given in Fig. 6. Boulders have been characterized by rock type and size. Boulder sizes (length of mean axis) have been divided into four categories: s (small) = ≤20 cm; m (medium) = 20—50 cm; l (large) = 50—100 cm; vl (very large) = >100 cm. Small sized boulders are easily picked up and car-

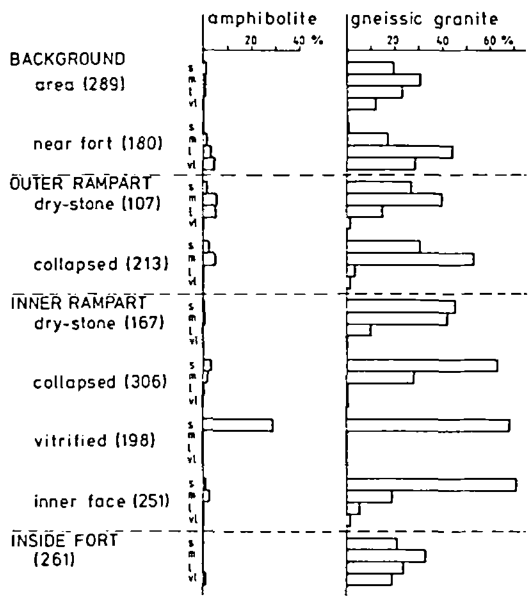

Fig. 6. Histograms of building material used at Broborg. Selective enrichment of small-sized amphibolite is most obvious.

ried, medium sized boulders would require major efforts and perhaps a helping hand. For moving large boulders, several men and possibly tools are required. Very large boulders, with weights exceeding 2.5 tonnes, are not the prime objects of major movements by man.

The background material (Fig. 6) was counted in the area more than 250 m away from the fort. Near (5—20 m) the fort, the number of small and medium sized boulders of gneissic granite are much smaller as compared to the background area. By contrast, boulders of these sizes are abundant in the outer rampart and, even more so, in the inner rampart, where small boulders dominate (Fig. 6). This illustrates that small to medium sized boulders from the surroundings were used for constructing the walls. Inside the fort, the distribution of gneissic granite boulders resembles the background distribution.

Amphibolite boulders are scarce in the background area, whereas near the fort they are more frequent, with some bias to larger sizes (Fig. 6). The outer rampart contains some amphibolite, particularly of small and medium size. The inner rampart has a low content of amphibolite, with the notable exception of its vitrified parts, where it is far more common than anywhere else (Fig. 6). Inside the fort, only very large amphibolite boulders are found — the smaller sizes have obviously been used for rampart construction.

Natural variations in the composition of the glacial drift could account for some of the differences observed. For instance, it is likely that the drift around Broborg originally contained more amphibolite than is represented by the background numbers. Natural variation is, however, insufficient to explain the predominance of amphibolite in the vitrified parts of the wall. It can be explained only by assuming a selective act of man.

Extent of vitrification

Already the casual observer notes that most of the inner rampart is vitrified. Blocks of vitrified masses occur frequently and the rampart is covered with a sandy material, derived from the disintegration of fire-cracked gneissic granite (Fig. 7), which results in a smooth topography of the rampart. Vitrified material covers almost the whole circumference (Fig. 2), with the possible exception of the area near the entrance, and two minor gaps in the northwest and southwest, which are covered with collapsed material. It is also quite obvious that amphibolite has played a major role in the vitrification at Broborg, as suggested by Kresten (1983): superficially molten amphibolite is frequent and the prominent

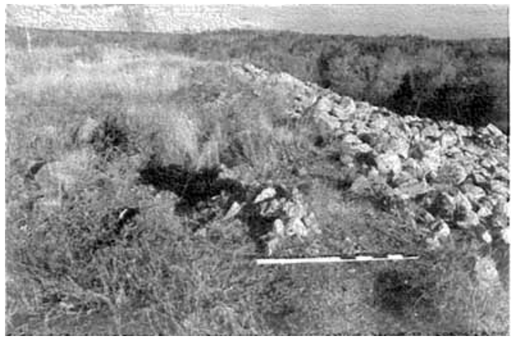

Fig. 7. Western part of the vitrified wall at Broborg (*c*, Fig. 2), showing blocks of vitrified material and disintegrated fire-cracked boulders of gneissic granite, which results in a smooth topography. Scale is one metre.

feature is abundant porous black melt, i.e., molten amphibolite.

On strong heating, the gneissic granite and the amphibolite behave differently. The gneissic granite contains primary magnetite which, on heating, is oxidized to hematite (or maghemite), causing a decrease in the susceptibility of the rock (Fig. 8). Amphibolite contains little or no primary magnetite. It melts incongruently to liquid + gas + spinel (in part, magnetite) ± mafic components (Yoder & Tilley 1962; Holloway & Burnham 1972), and the susceptibility increases strongly (Fig. 8). The overall susceptibility of the vitrified wall increases.

Therefore, a magnetometric survey of Broborg

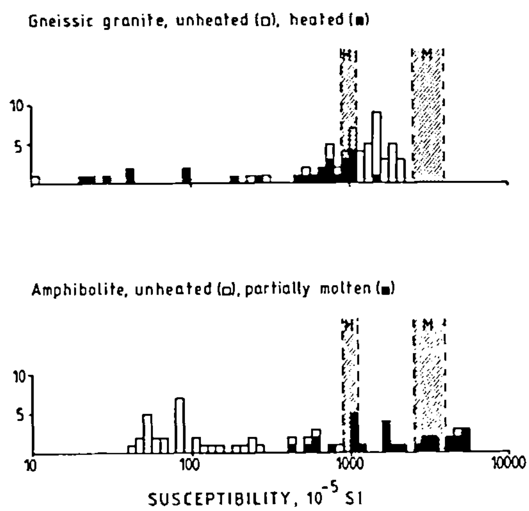

Fig. 8. Histograms of magnetic susceptibilities of boulders from the inner rampart and inside the hill-fort. H = susceptibility range for hematite; M = susceptibility range for 1 % magnetite. Heating results in decreased susceptibility for gneissic granite (oxidation), and increased susceptibility for amphibolite (formation of magnetite by partial melting).

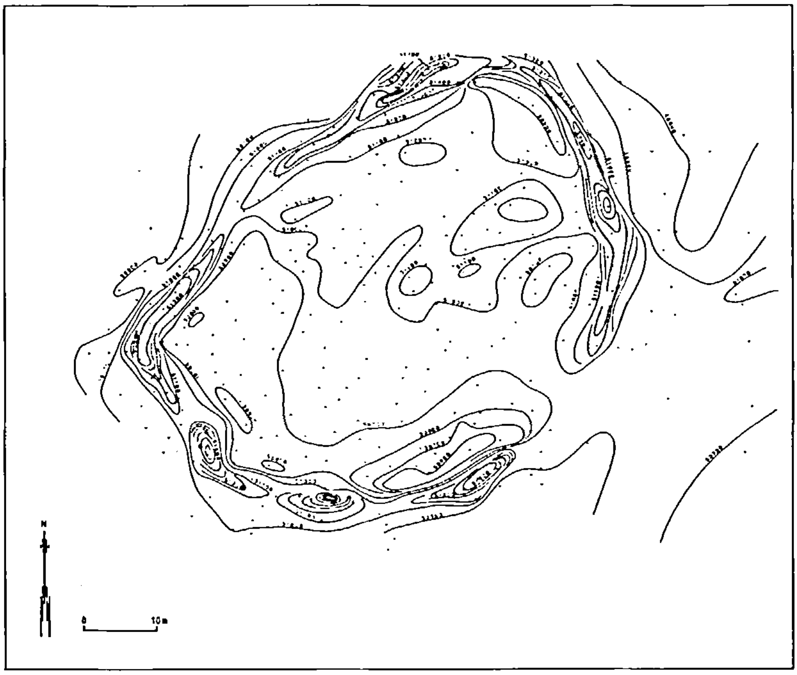

Fig. 9. Magnetometric map of Broborg, same area as shown in Fig. 2. Points of measurement marked by dots. Contour intervals 100 nT, screened areas >51200 nT.

was carried out in order to verify the extent of the vitrification. A Scintrex MP-2 proton magnetometer, recording the total magnetic field with a resolution of 1 nT, was used. Aerial photographs were used to locate arbitrary points of measurement (Fig. 9), with a spatial accuracy better than one metre. Drift was checked by repeated measurements at fixed points and checking with the Lovö Observatory recordings, which showed a smooth rising trend of about 30 nT during the measurement time.

The magnetometric map shows that high magnetic levels occur only in connection with the vitrified rampart (Fig. 9). It confirms the results of the field study, with the exception that vitrification is indicated at the "southwestern gap", covered by debris (Fig. 2). Vitrification covers the entire circumference save for the entrance area and a minor gap in the northwest (Fig. 9).

Modelling was carried out using the "Gamma" program developed by the Swedish Geological Company, the Geological Survey of Sweden, and the Luleå University of Technology, along a NNW—SSE profile from about point *e* to just west of the entrance (Fig. 2). The results indicate that the hill has a core of gneissic granite, overlain by moraine, which is about 5 m thick in the NNW (scour-side of the ice), and 10—30 m thick in the SSE (lee-side moraine). Least moraine cover is indicated just south of the northern rampart in the section. Within the hill-fort, large boulders of gneissic granite account for the magnetic variations observed. The magnetic anomaly above the vitrified section is explained by a vitrified layer, 150 cm wide and 40 cm thick. In the northern part of the section, a large boulder of gneissic granite at the inner face of the wall is assumed to explain the magnetic pattern observed.

A provisional trench through the vitrified wall (*a—a'*, Fig. 2), commenced in 1982 (Löfstrand 1983) and further excavated in 1985, confirmed the amphibolite as the source of the black porous melt cementing and penetrating blocks of fire-cracked gneissic granite (Figs. 10, 11). Vitrification was found only at the top layer, about 70 cm thick, along the inner face of the inner rampart, as shown in Fig. 2. Open spaces in the dark melt showed abundant 'wood casts' (Fig. 11A).

Further down, only fire-cracked boulders of gneissic granite were found (Fig. 12), underlain by similar boulders, apparently unaffected by heat. The inner face of the wall was constructed with larger, equidimensional blocks (40—60 cm) of gneissic granite. Vitrification along the inside top of the inner rampart, underlain by fire-cracked gneissic granite, caused the frequent formation of hollow space beneath the vitrified layer (Fig. 13A), which forms a solid roof. These hollows most likely formed by the disintegration of the fire-cracked gneissic granite.

Fig. 10. Top part of trench *a—a'* (Fig. 2) showing partially molten amphibolite. The resulting black, porous melt pours down on and is penetrating the fire-cracked boulders of gneissic granite.

Particularly within the uncovered part of the inner rampart (from the trench *a—a'* to *b*, Fig. 2), it is clear that the vitrified parts of the wall were built in boxes, about 2 m long and 1—1.5 m wide (Fig. 13). The boxes, containing vitrified masses, stand up in relief, whereas the connecting seams form depressions in the relief (Fig. 13B).

Chemistry and petrography of the vitrified material

So far, 44 chemical analyses (mainly microprobe) have been carried out on material from Broborg, the detailed results of which can be obtained from the first author. The vitrified material consists of glasses, opaque, brown or colourless in thin section, containing crystallized olivine, pyroxene, spinel, and ilmenite. In addition, droplets of (once molten) pyrite are found, particularly in the colourless glass, and droplets of iron (Fig. 14) in the opaque glass, particularly when adjacent to wood casts, indicating reducing conditions.

The analyses confirm that the opaque (black) glasses are derived from the melting of amphibolite and subsequent fractionation of spinel, olivine, or pyroxene. Fig. 15 shows the evolution of the melt from the earliest drop of liquid found in the amphibolite (1) to the final liquidus composition (3), analyzed from one amphibolite block with increased melting downwards. All melts deviating from this path are satisfactorily explained by fractional crystallization of olivine and/or pyroxene and/or spinels. Colourless feldspathic glasses are formed by the incipient melting of gneissic granite (Fig. 15), with the brown glasses representing the results of limited miscibility between the colurless and opaque glasses.

Some of the analyses of opaque glasses show elevated contents of phosphorous — about 1.2 % P_2O_5. As analyses of amphibolite have P_2O_5 levels between 0.19 and 0.33 %, phosphorous seems to have been added.

Correct temperature estimates are important for interpreting the process of vitrification. Previous estimates for vitrified forts (Brothwell et al. 1974; Youngblood et al. 1978; Fredriksson et al. 1983) are based upon phase diagrams, which do not include minor but rather important phases such as fluorine and phosphorous. Using the same method for the colourless (feldspathic) glasses from Broborg, liquidus temperatures in the range of 1060—1075°C are arrived at. This method is only applicable to quartz—feldspar-rich glasses and cannot be applied to the opaque glass.

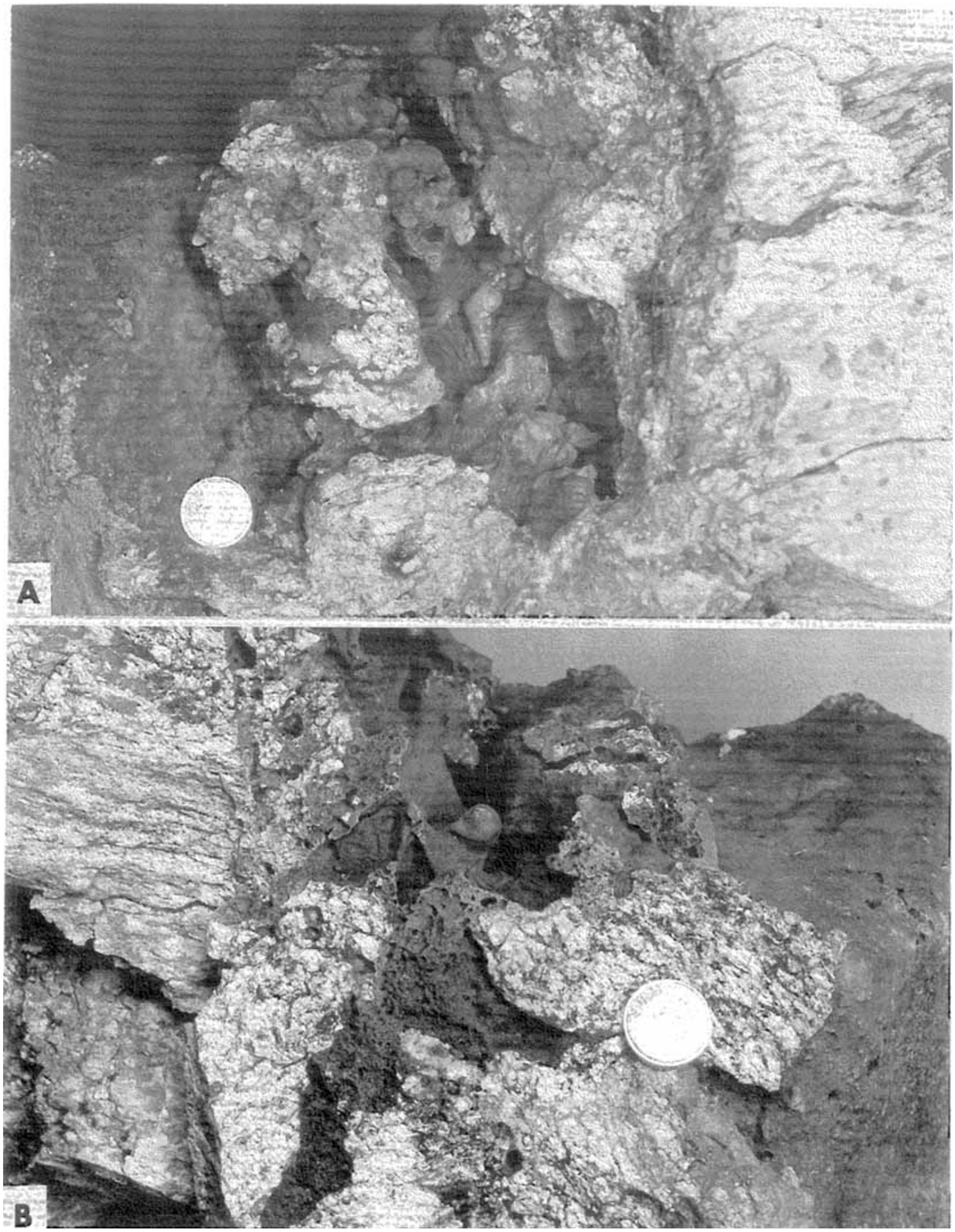

Fig. 11. □ A. Close-up of vitrified material (Fig. 10) showing abundant 'wood casts' in molten amphibolite, which most likely are casts of charcoal. □ B. Reverse side of sample, showing highly porous black melt penetrating and cementing the cracked gneissic granite. Note that most of the dark stringers in the gneissic granite consist of black melt. Diameter of coin (SEK 10) is 20.5 mm.

Fig. 12. Front of trench *a—a'* (Fig. 2), about half-way through the vitrified layer. Vitrification is found at the top 30 cm layer, underlain by fire-cracked gneissic granite.

Fig. 13. ☐ A. Vitrified wall (from *b* to the trench *a—a'*, Fig. 2) showing cavities underneath vitrified layer (bottom part, centre), as well as box-type structure (about 1×2 m) of the vitrified wall. To the left, dry-stone outer face, to the right, sloping inner face of rampart. ☐ B. As above, viewed from the side, with upper contours of rampart outlined in ink to emphasize box-type structure. Scale is one metre.

We have determined the melting points of various vitrified products and their parental rocks by differential thermal analysis (DTA) in static air atmosphere. The results are given in Table 1. The values are given as T_i, temperatures at the projected intersection of the solidus (= beginning of melting). The temperatures are taken as minimum temperatures required for the process. Whenever parental rocks and resulting vitreous products had been analyzed, such as for Borgaberget and Borganäs, the data pair shows almost the same temperature (Table 1; note that Borganäs melt contains some P_2O_5 from bones, lowering the melting point). Other details show that melting points as determined by DTA are meaningful. At Dun MacUisneachan, angular fragments of medium grey, porous melt are included in dark grey, porous melt. The former gives a somewhat higher melting point than the latter, as expected from the setting. The overall spread of solidus temperatures for vitrified materi-

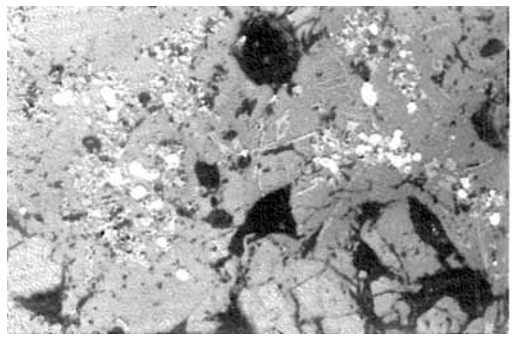

Fig. 14. Broborg, sample BR4, locality *c* (Fig. 2). Globules of metallic iron (white) associated with spinel crystals (grey) in a groundmass of opaque glass with lamellae of plagioclase (darker) and pyroxene (lighter). Micrograph, reflected light, field of view is 0.36×0.55 mm.

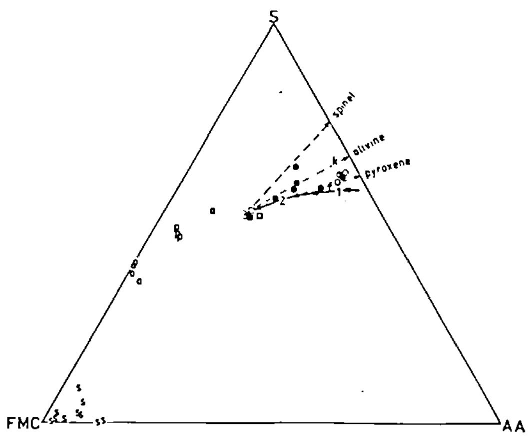

Fig. 15. S (SiO_2)–FMC (TiO_2+FeO+MnO+MgO+CaO)–AA (Al_2O_3+Na_2O+K_2O) plot for Broborg. Original phases are K-feldspar in gneissic granite (k), amphibole (a) and feldspar (f) in amphibolite (filled square). Phases formed during vitrification are colourless (open circles), brown (half-filled circles) and opaque (filled circles) glasses, crystallized pyroxene (p), olivine (o) and spinels (s). Liquid evolution proceeds from 1 via 2 to 3. Open squares are average glasses. Trends for changes in liquid composition with fractional crystallization of spinel, olivine and pyroxene are indicated by broken arrows.

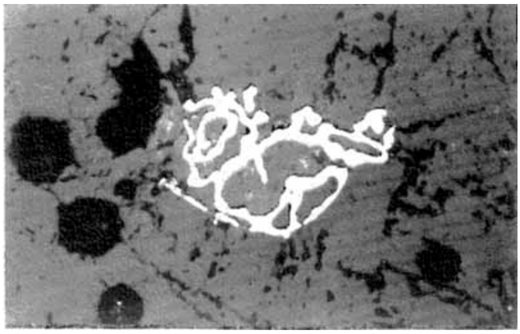

Fig. 16. Norsborg, sample NO4A. Iron sponge (white) in opaque, not crystallized glass. Micrograph, reflected light, field of view is 0.36×0.55 mm.

als from various sites is 1066—1235°C (Table 1).

The solidus temperature for the opaque (black) vitreous material from Broborg is 1165°C. Repeated heating and cooling of the sample yield a reproducible melting temperature of 1130°C. Crystal-liquid equilibration temperatures, using the calibrations by Leeman & Scheidegger (1977) for the distribution of Fe between olivine and glass give a range of 1017—1078°C for Broborg samples. Available data suggest that equilibrium has been attained in the samples, suggesting prolonged, rather than rapid, heating processes. Equilibration temperatures are expected to be generally lower than melting temperatures as they reflect crystallization and equilibration during cooling of the melt.

The partial pressure of oxygen can be estimated from the paragenesis, i.e., a siliceous glass, fayalite (in olivine), magnetite, and iron. Relevant phase diagrams (Lindsley et al. 1968) indicate partial pressures of oxygen of about —13.5 or less (log fO_2), at 1130°C, which is at the high-temperature end of the conditions encountered for ancient iron slags (Kresten 1984).

The temperatures required for vitrification demand a strong wind, or forced draught. But this does not seem to be sufficient. A small-scale experiment, using gneissic granite and amphibolite from Broborg in an open charcoal furnace did not produce vitrified material even when applying forced draught for several hours (Kresten 1983). Both rock types merely fire-cracked in the white heat. Only when the furnace was sealed with grass turf and forced draught was applied, vitrified material readily formed. This confirms that water plays a major role in the melting of amphibolite (as well as most other rocks). All pores in the amphibolite melt (Fig. 11B) where once filled with supercritical vapour. In an open hearth, water escapes and melting does not occur until even higher temperatures are reached. Therefore, vitrification at Broborg required both forced draught as well as a confined space.

Summary and discussion

We have established that the vitrification at Broborg is found around the whole circumference, with few gaps only. The phenomenon is caused by molten amphibolite penetrating and cementing the fire-cracked gneissic granite, which is only superficially molten. Thus, vitrification at Broborg is dependant upon the abundance of amphibolite in the wall. Vitrification occurs along the inner face of the inner rampart, forming a cake of about 40—70 cm thickness, 1—1.5 m width. Beneath the vitrification, hollow space frequently occurs.

There has been a selection of building material at Broborg, both with regard to size and quality. Selectivity with regard to the vitrified parts of the wall is even higher than apparent from Fig. 6, as fire-cracked gneissic granite may be counted more than once, and molten amphibolite is not counted as boulder at all. Thus, 50—50 proportions between amphibolite an gneissic granite are perhaps more realistic. Such a selection bears witness on a deliberate act of man.

By contrast, the surveys by Nisbet (1974, 1975) on the building material of Scottish vitrified forts have shown that "more fusible kinds of rock were not (as has sometimes been postulated) specially selected for the walls of the fort which subsequently became vitrified" (Nisbet 1982, p. 26). For Broborg, selection of amphibolite, the necessary prerequisite of vitrification, is not postulated but considered by us as a fact (Fig. 6).

Temperatures required are about 1130°C for Broborg, which is with in the range of melting points for vitreous products for a numer of forts (Table 1) and temperatures estimated from other investigations (Nisbet 1974). Strongly reducing conditions are advocated by the occurrence of metallic iron, which also has been reported to occur in other vitrified walls (Youngblood et al. 1978). Besides Broborg, the following Swedish sites have been found to contain metallic iron: Darsgärde, Ullavi Klint, Norsborg (beautiful iron sponges, Fig. 16), Sjöhagsberget, and Ekhagen (Fig. 1).

Fluxing by phosphorous (i.e., bones) may or may not have occurred at Broborg. At Kollerborg (Fig. 1), a maximum P_2O_5 content of 13.8% (!) has been found, which can be explained only by the addition of bones to the system. Several other Swedish sites (Nyby, Stenby, Borgaberget, Norsborg, Fjället; Fig. 1) show elevated phosphorous contents as well, which are not explained by partial melting

Table 1. Melting temperatures (onset, first heating) of vitrified and parental material from various sites. DTA, 10°/min, static air atmosphere. Samples of Scottish, French and German vitrified forts have been put at our disposal by British Museum, London (BM-numbers) and by the Smithsonian Institution, Washington, D.C.

Number[1)], Fort, Province, Class[2)]	Sample	T_i, °C	Remarks
Sweden			
SWE002 Darsgärde, Uppland, V	DG1	1090	melt
SWE003 Broborg, Uppland, VF	BR1D	1165	melt
SWE004 Nyby, Södermanland, V	NB2	1080	melt
SWE005 Stenby, Södermanland, V	SB1	1140	melt
SWE006 Kollerborg, Närke, VF	KB4	1110	melt
SWE008 Borgaberget, Närke, V	BO1	1130	basic melt
	BO2	1130	basic rock
	BO3	1080	acid melt
SWE009 Ullavi Klint, Närke, V	UK1	1190	glazed rock
SWE010 Norsborg, Värmland, VF	NO2	1150	melt
SWE011 Männö borg, Södermanland, V	MN1	1080	basic rock
SWE012 Sjöhagsberget, Uppland, V	SJ2	1170	melt
SWE013 Fjället, Uppland, V	FJ3	1120	melt
SWE014 Ekhagen, Uppland, V	EK1	1170	melt
- - Borganäs, Dalarna, MF	BN2	1050	melt
	BN3	1070	brick
Ireland			
IRL001 Banagher Glebe, Ulster, VF	BG1	1150	acid melt
	BG3	1140	basic melt
Scotland			
SCO001 Finavon, Angus, VF	BM1975,P7(1)	1235	melt
	F-2	1210	melt
SCO009 Mote O'Mark, Kirkudbridge, VF	MM-2	1128	melt
SCO028 Dun MacUisneachan, Argyll, VF	BM1936.40	1155	melt fragment
		1115	melt matrix
SCO039 Ard Ghaunsgoil, Inverness-shire, VF	BM1985,P36(1)	1139	melt
SCO050 Craig Phaidrig, Inverness-shire, VF	BM1975,P7(11)	1210	melt
	CP-5	1193	glazed rock
SCO057 Cullykhan, Banffshire, VF	BM1974.P9	1215	melt
SCO058 Dunnideer, Aberdeenshire, VF	D-6	1200	melt
SCO059 Tap o'Noth, Aberdeenshire, VF	BM1975,P7(7)	1235	melt
	TN-4	1200	melt
SCO082 Braes, Stirlingshire, VF	B-2	1235	melt
SCO083 Abbey Craig, Stirlingshire, VF	AC-4	1112	melt
France (north-west and central)			
FRN001 Château Gontier, Orne, VF	LC-1	1196	melt
FRN008 Camp Anglais, Mayenne, VF	SS-B	1188	melt
FRC004 Châteauvieux, Creuse, VF	CH-1	1086	acid melt
FRC005 Puy de Gaudy, Creuse, VF	PG-2	1066	glazed rock
FRC007 La Tour, Creuse, VF	LT-6	1180	melt
Germany (west)			
GEW001 Donnersberg, Rheinland-Pfalz, VF	DO-14	1086	glazed rock

1) Register of European vitrified forts (Kresten & Kresten, unpublished)
2) VF = confirmed as vitrified fort, V = vitrification occurring, MF = Medieval fortification

of parental rocks. High phosphorous contents in glasses from vitrified forts were previously reported by Youngblood et al. (1978) from Puy de Gaudy, France. At Rahoy, Argyll, Childe & Thorneycroft (1937*a*) report bones to have been included in the rubble filling which vitrified. Addition of phosphorous to the system would result in lower melting temperatures and lower viscosities (= fluxing), which would be beneficiary for the melting/cementing process, whether it was intentional or not.

The amphibolite melt contains ample *wood casts*, reported also from several other sites (Youngblood et al. 1978; Nisbet 1982) and found to occur at Nyby, Stenby, Norsborg and Sjöhagsberget in Sweden (Fig. 1). The trial trench at Broborg showed that hollows at the base of the vitrified layer, measuring about 20×20×10 cm (Fig. 11A) were crowded with wood casts. Most wood casts are 3—

5 cm long, 2—3 cm wide, with straight terminations. One could speculate whether the casts are those of wood, or rather those of charcoal. Broken wood splinters, it does not break along straight terminations. No signs of wood splinters have been encountered at Broborg. When both wood and charcoal are used in iron smelting, casts of either fuel in the slag can clearly be distinguished from the other (E. Hjärthner-Holdar, pers. comm.). At the present stage of investigations, we have to assume that charcoal has formed the fuel necessary for the vitrification at Broborg.

Broborg is *vitrified all around,* save for one or two possible gaps, with the notable exception of the entrance. If an enemy was to storm a fort, the entrance, probably closed by wooden constructions, would be a prime target. Defendes most likely realized this and reinforced the entrance by an outer rampart (Fig. 2). There are indeed several forts known, where vitrification seems to be confined to the entrance area: An Dun and Harelaw in Scotland (Cotton 1954), Castle Bank (Alcock 1972), and Caer Cadwgan (Austin et al. 1988) in Wales.

Vitrification at Broborg occurs only along the inner face of the inner rampart. From the outer edge of the vitrified mass to the outer dry-stone face of the wall, there is between 2 and 4 metres unvitrified space which, where preserved, shows a dry-stone setting. Known standing palisades, which is one of the prime candidates for the fuel required for the vitrification, are placed along the outside face of the ramparts (Buchsenschutz & Ralston 1981). A palisade placed several metres into the rampart would indeed not be an optimum defence construction. This leaves us with "Ehrang" or "*Murus gallicus*" type walls (Buchsenschutz & Ralston 1981); which have timber constructions throughout the walls. Such constructions seem lacking at Broborg.

How was it possible at all to vitrify almost the entire circumference of the wall? In the 'destructive model', an attacking enemy would have been forced to wait for a suitable strong wind, coming from all sides (a tornado?) before setting fire to the palisade/timber frame construction, which we find no signs of. Else, we have to assume a huge timber construction inside the fort — which we have no evidence for — burning violently and causing a chimney effect.

Another possibility is that the enemy was equipped with bellows. Several Irish tales, e.g., *Mesca Ulad,* tell us that houses under siege were stuck on fire; 150 blacksmiths with their bellows provided forced draught (Thurneysen 1921, p. 473).

Much of the knowledge required to fuse rocks stems from metallurgy, such as the use of bellows to a confined space (= the furnace) and the use of fluxes. Adding bones to lower the melting point of rock melts is by no means more advanced than adding slag formers to the ores, or adding tin to copper to obtain bronze — methods which existed several thousands of years before the formation of vitrified forts.

The wall had to be vitrified in sections, rather than in one single piece. The box-type structures (Fig. 13) may represent such sections. This would imply a *constructive vitrification.*

A possible scenario is the following. A top layer consisting of about equal parts of amphibolite and gneissic granite, with beds of charcoal (Figs. 9, 10) was ignited. Forced draught was applied by bellows from the outside of the rampart, with the soil-covered inner face and top providing the necessary confined space, similar to a metallurgical furnace.

Whether this scenario is accepted or not, we consider a constructive formation of the vitrified rampart at Broborg to be indicated by the evidence put forward. The investigation of Broborg has shown that there still remain several question marks regarding vitrified forts, which require further research and excavations. Each occurrence has to be evaluated from available facts, and broad generalizations to cover *all* vitrified forts are uncalled for.

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