Proc Soc Antiq Scot, 116 (1986), 17–40

The Yorkshire Television vitrified wall experiment at East Tullos, City of Aberdeen District

Ian Ralston*

ABSTRACT

Experimental firing of a full-scale model of a pine-laced wall provoked limited localized vitrification of the hearting. The results may be added to previously-garnered evidence to refute the suggestion that vitrification was constructional in intent. The large-scale vitrification of some Scottish sites must have provided a spectacular intimation of destructive power.

INTRODUCTION

During late March and early April 1980, a timber-laced wall, corresponding approximately to a later prehistoric type, was reconstructed on the margin of the City of Aberdeen District Council Cleansing Department's waste disposal tip at Tullos Hill, Aberdeen City District, with a view to attempting to reproduce experimentally the characteristics of the vitrified walls recorded in north Britain. The project was financed totally by Yorkshire Television, a division of Trident Television, and justifiably work on the wall had to comply with the necessities of a tight filming schedule. Although firing of the wall took place in less than optimum conditions, and although the wall had to be demolished in its entirety some 28 hours after its ignition (when it was still alight), small quantities of vitrified rock were obtained. This reconstruction and its subsequent firing formed part of one episode of *Arthur C Clarke's Mysterious World*, broadcast in the autumn of 1980.

A principal difference from the walls built by Childe and Thorneycroft for the experiments reported in these *Proceedings* (1938a, 54) was the intention to build the East Tullos wall at approaching full scale. The larger of the 1930s' experimental walls – that at Plean Colliery – measured 12 ft (c 3·65 m) long, by 6 ft high (c 1·82 m) and the same broad. Whilst wall breadths in excess of 6 m have been recorded in excavation, as, for example, at Craig Phadraig, Inverness District (Small & Cottam 1972), such dimensions appear to represent broader-than-average constructions, and so East Tullos was built to a basal width of 4 m.

Childe and Thorneycroft's experiments demonstrated that localized vitrification could be provoked simply by setting fire to a timber-laced wall. Despite this demonstration, the theory of 'creative vitrification' – the hypothesis that vitrification was a constructional process to strengthen walls – has lingered on. In its minimalist form, the latter theory can be expressed as follows: despite the absence of analytical evidence that the vitrified walls contained anything except wood and stone (and, doubtfully, bone, discussed below), it seems unlikely that vitrification could be produced simply by the combustion of timber-laced walls. Some of the conclusions of the most sanguine of the

* Lecturer in Archaeology, University of Edinburgh

laboratory-based reports available at the time of the experiment are worth quotation *in extenso*, since they run counter to the Childe-Thorneycroft view:

> 'The temperatures necessary for partial melting are in the range of >900–1100°C. These high temperatures, while not serving as direct proof of a constructional intention, do preclude the hypothesis that vitrification resulted from simply setting fire to a timber-laced wall of *murus gallicus* type' (Youngblood *et al* 1978, 119–20).

It was this contrast in views which constituted 'the mystery' that attracted the Television Company's attention. It is necessary first of all to dispose of the *murus gallicus* label. In recent discussions of the vitrified forts, this epithet implies nothing more than the inclusion within the wall-core of horizontal timbers disposed longitudinally and transversally – the timber-laced wall of Scottish terminology. The latin name is a survival from the time when Scottish Iron-Age material was compressed into an ultra-short chronological span, and when derivation of the Scottish series of fortifications with internal timberwork from those of late la Tène France, encountered by Julius Caesar at Avaricum (Bourges, Cher) in 52 BC, seemed a tenable position. True *muri gallici* – often identified archaeologically by the presence of long iron spikes, presumably augered into the intersections of their longitudinal and transversal timbers – remain resolutely late in the West European sequence. Early examples may date to the second century BC. Radiocarbon determinations have made it plain that the Scottish series of fortifications begins at a much earlier date, so that the retention of this term cannot be justified, especially as architectural variants on the stone/earth/timber theme have increasingly been recognized on the Continent as in Britain.

A recent review of the archaeological record from excavations (MacKie 1976, 206–10) has indicated the strength of the field evidence for vitrification as a product of the destruction of defences. The writer concurs entirely with MacKie's arguments in this regard. The theories that have previously found favour are equally outlined by Nisbet (1974; 1975), who also presents the most thorough data set yet assembled to demonstrate that vitrified works display no evidence for the selection of particular geological types, but are rather built of the materials that were available locally. These three papers (MacKie 1976; Nisbet 1974; 1975) contain all the most cogent arguments that have been advanced to suggest that vitrification is a destructive process, frequently coinciding – in archaeological terms – with long-term, if not definitive, abandonment of the affected site. The East Tullos experiment provided an opportunity to review afresh the practicalities, previously considered by Childe and Thorneycroft (1938a) on the basis of their experimental work, of provoking vitrification in a wall containing an internal timber framework.

THE CONSTRUCTION OF THE WALL

The design of wall finally selected for construction and the materials employed were chosen partly on the basis of the knowledge of the timber-laced and vitrified forts of Scotland and elsewhere and partly on the basis of expediency. The materials were obtained by Mr Nick Lord, Researcher at Yorkshire Television.

The European heritage in stone-earth-and-timber-built ramparts is a rich and varied one (Büchsenschütz & Ralston 1981), with many of the better-preserved examples displaying indications of burning on excavation. Vitrification of these works has been noted widely on the Continent as well as in Scotland in areas with appropriate geologies, there being, for example, an extensive series of sites in France (Ralston 1981; Büchsenschütz 1984, 227–30, fig 104). Whilst there are certainly differences within the set, as Déchelette (1913, 704–13) noted, it is certainly not the case that the Scottish vitrified sites are 'unique in Europe' (MacKie 1976, 206).

Before the reconstruction took place, Mr Lord and the writer sought advice from Dr Olivier

Büchsenschütz (CNRS, France), Professor Fred Glasser (Chemistry Department, University of Aberdeen), Mr Peter Hill (Edinburgh), Mr David Longley (then Teaching Fellow at the University of St Andrews), Miss Helen Nisbet (Lasswade) and Dr Elizabeth Youngblood (Arizona State University). Whilst we are grateful to them all for their assistance, none of them bears any responsibility for the eventual form of the wall, nor for the conduct of the experiment.

In essence, three possible designs for the wall were considered, a major variant in each option being the spacing of the timbers to be incorporated. The distribution and size of the timbers are clearly of predominant significance in determining the amount of combustible material in the wall, whilst the disposition of the timbers conditions the ease with which they may be ignited. The designs were, first, the timber-laced wall, as most commonly identified in Scotland, with transversal and longitudinal beams (but not vertical elements and no jointing of the timbers) – essentially the Ehrang type (Collis & Ralston 1976) of Continental Europe. A variant of this, incorporating vertical timbers set in individual postholes, and positioned in the external wall-face, interspersed with panels of stonework, was the second option considered. Again such architecture is widely known, although, generally speaking, the recovery of upright timbers in defensive wall constructions is a feature more of central than of western Europe, and is more frequently documented in excavation in southern than northern Britain. Exceptions, however, occur in some numbers; the entranceway at Cullykhan, Banff and Buchan District (Greig 1972) may be cited by way of example. Reconstruction drawings of such walls, with the vertical posts providing the major supports for a breastwork, added to the potential attraction of this design. The third model, essentially based on the author's own excavations of a Pictish fortification at Green Castle, Portknockie, Moray District, equally has the merit of exposed vertical elements, which it was believed would have been of assistance in actually setting the wall alight. This rather elaborate variant (Ralston 1987) consists of a framework of prefabricated 'boxes' of vertical, longitudinal and transversal timbers, around which the stonework could have been erected subsequently. Since the timber framework could have been constructed under cover, this design was proposed in the event of inclement weather during the building stage.

Despite suggestions that it would be very difficult to ignite the wall in the absence of exposed vertical structural timbers, constraints of labour availability and of time, and the intention to use machinery to speed construction, prompted the eventual selection of the basic timber-laced wall incorporating only longitudinal and transversal beams. Furthermore, the prohibitive costs of hardwoods, more particularly oak, dictated the choice of scrap Columbia pine for the transversal elements, and rather less substantial pine for the longitudinal elements. The main transversal beams, trimmed by chainsaw, were approximately 5·5 m long; these beams measured approximately 0·23 m by 0·12 m (9 in by 5 in). The lengths of pine supplied for use as longitudinals were of the order of 4 m; these had to be stitched together, using 4 in (0·10 m) wire nails, to run the entire length (about 6·5 m) of the reconstructed section of wall. The longitudinals were either 4 in by 4 in (0·1 m by 0·1 m) in cross-section, or 4 in by 3 in (illus 1). The preparation and insertion of the timberwork were organized by Mr George Blackhall.

The stonework comprised a variety of materials. Most of the facing-stones of the wall were obtained from a drystone dyke which had been demolished in the area: these were predominantly granites. The bulk of the hearting consisted of gabbros from Balmedie Quarry, Gordon District; these gabbros included both head-sized stones and smaller chips, the latter usually 0·10 to 0·15 m in length. This plutonic rock was selected on the advice of Professor Glasser: it displays 'ready flow' at a relatively low temperature (Nisbet 1975, 5). Stones of equivalent size were also obtained from Cove Quarry (City of Aberdeen District) in a metamorphic rock, a quartzose mica-schist. Some of the larger gabbros were required for the wall faces; most of the little stones were employed in the upper layers of the hearting – particularly from the third layer of transversal timbers upwards. The building

ILLUS 1 An early stage of the construction, looking north. The second row of longitudinals is visible on the surface

of the wall-faces was undertaken by Mr Robin Callander, who also supervised the remainder of the construction.

Site preparation and wall construction occupied approximately four cold, blustery and intermittently very wet days in late March. The site selected for construction was a low gorse-and-grass-covered knoll (altitude approximately 80 m) a little to the west of the triangulation point on Tullos Hill (NGR NJ 956 037). The gorse was removed prior to construction but no effort was made to strip the turf. The wall was built in three and a half days by a squad of seven, who also had to transport the bulk of the materials to the site along a muddy track from a drop-point some 300 m away. A Leyland tractor with rear-mounted shovel and trailer, and an International tractor with front-mounted shovel which could be raised vertically were used. It is thus impossible to arrive at an accurate estimate of the time that would have been taken had only appropriate prehistoric technology been employed. The crew worked long days (08.30–18.00 hrs) and the time spent in site preparation, transport of materials, and construction may be estimated at 30 man-days – perhaps not much less than would have been required (excluding transport of materials), had animal traction been available to help to lift the upper transversal beams. Much of the small hearting material used in the upper part of the wall was lifted by machine (illus 2), and then spread by hand. Childe and Thorneycroft (1938a, 46, note 1) identified certain practical merits in the inclusion of such small angular rubble. At East Tullos, a disadvantage of the use of this material was that some soil, incorporated in the loads that were brought to the site, was incidentally employed in the make-up of the wall and subsequently contributed locally to smothering the fire. However, had the hearting material consisted of larger lumps of stone, it is possible that the total man-days required would not have been very different from what was actually achieved, assuming the materials necessary to have been available on site, since two of

ILLUS 2 Small gabbro chips being added to the hearting of the upper part of the wall

the crew were employed essentially in moving wood and stone to the place of construction. The estimate may be presented thus:

> Actual time taken in building wall (as opposed to transporting material to the site): 3·5 days for 5 workers=17·5 man-days.
> Additional time required for manual positioning of upper courses of transversals (35 beams): 1 day for 5 workers=5 man-days.
> Dyker's estimate for the additional time required to place large gabbros as hearting (as opposed to the chips actually supplied)=7·5 man-days.
> Total: 30 man-days.

The sector of wall was built with its long faces running south-east/north-west, with the intention that the most likely winds – either from the south-west or off the sea – would blow at right-angles to the wall. It was hoped that air currents from either of these directions would encourage the transversal timbers to burn back into the wall core. At ground level, the wall was some 9·4 m in length and 4 m wide; the width tapered in to approximately 3·3 m at the summit. The wall was generally 2·45 m high, but locally reached 2·9 m because of the sloping nature of the terrain.

Only the central portion of the wall was timber-laced; this was some 6·75 m long. Both ends were rounded-off purely in drystone construction, in an effort to minimize the effects of draughts and heat loss, which would have been absent in the continuous wall-lines of the original vitrified forts themselves. Once the area of operations had been defined by the construction of the basal course of stonework, dykers, carpenters and core-fillers were able to work in tandem with minimal disruption to each others' efforts. The facings were built only one stone thick, and were not bonded into the core as thoroughly as the dyker would have liked, had more time been available for the construction. The selection of stones to bridge across the beam-ends was successfully achieved; the general quality of the drystone construction was borne out in due course by its solidity when fires were lit against it.

The first layer of timbers was inserted almost at ground level: eight of the slender timbers were evenly spaced out and arranged parallel to the principal wall faces; each subsequent horizon of longitudinal timbers used the same number of elements. The hearting at this level consisted essentially of the more substantial gabbros. The initial layer of transversals was incorporated at approximately 0·5 m above the ground surface, though this varied because of the sloping nature of the site. Each subsequent horizon of transversal timbers was off-set slightly, so that the centre-to-centre distance between the end transversals in the second horizon was 6·2 m. Moreover, the transversal beams in the second and third layers were set end-on, since it was felt that this might subsequently be of use in coaxing the beam-ends to ignite. In all, four rows of transversals were employed: 12 beams were placed in each of the three bottom rows, and 11 in the uppermost. The vertical separation of these beams, centre-to-centre, was (from bottom to top) 0·50 m, 0·50 m and 0·55 m. Exact distances were of course determined by the nature of the wall coursing. Midway between each row of transversals, a horizon of eight longitudinals was inserted, and a fifth row of longitudinals overlay the top horizon of transversals, this uppermost set of timbers being sealed by a final layer of stone chips, before the rampart was finally capped with a thin (0·10 m thick) layer of turf and soil (illus 3). It may

ILLUS 3 The wall nearing completion; measurement in progress as the final capping is spread on the wall-head

be noted that none of the horizons of longitudinal and transversal timbers was in contact with each other.

In addition to this structural timber component, various off-cuts from the transversal beams were also put into the core. Such items were used for example to chock the horizontal structural timbers while the hearting was built up around them. It was also suggested to us that it might be advantageous to roughen the surfaces of the transversal timbers with an axe or adze to enable fire to spread along them more readily, but again this proved impossible to achieve because of time constraints: in retrospect, this would seem to be an unnecessary refinement. In sum, the volume of timber placed in the wall may be estimated at a little under 8 cubic metres, for a wall approximately 62 cubic metres in total volume. The amount of softwood employed was thus of the order of 14% of the total volume of the wall. Nisbet has estimated that 25% wood must have been incorporated in the subsequently-vitrified wall at Langwell (1982, 26). At Plean Colliery, the pit-props used by Childe and Thorneycroft (51 transversals and 20 longitudinals) are estimated to have represented some 2·15 cubic metres of timber, weighing one ton. In that experiment, a further 6 cwt of timber was used in the packing of the wall-core, and therefore it is legitimate to add 30% to the above calculation of the volume of timber, to give a total timber volume of about 2·8 cubic metres. The total volume of the wall must have been approximately 12·1 cubic metres, so that the wood content was of the order of 23%. Childe and Thorneycroft's figures for the weights of materials used (7·35 tons of stone and 1·3 tons of wood) suggest that the wood constituted about 15% of the total weight.

The only metal deliberately placed in the East Tullos wall was a set of narrow steel tubes, three along each principal face, to allow thermocouples to be inserted and withdrawn. These penetrated at right angles to the principal wall-faces and ran approximately 1·80 m into the hearting; they were positioned at the level of the second row of transversals, approximately 1·10 m above ground level. Various extraneous pieces of iron, notably bolts and nails attached to the timber that was supplied, were also incorporated into the wall, as we had insufficient manpower to remove them, but these elements were quantitatively insignificant. Iron items have rarely been recovered from vitrified walls. Only one case has been documented in Scotland (Nisbet 1975, 3); and there is only one French example known to the author, at La Courbe in Orne (Ralston 1981, no 91); here, the observation, originally due to Coutil, has been borne out by recent work (Mlle C Peuchet, pers comm).

Had time permitted, we had intended to cloak the wall-faces with turves, since, in various contacts' opinions, such a coating would have helped to impede air flow through the wall, thereby contributing to the achievement of higher temperatures in a somewhat oxygen-starved environment in the core of the wall. Since such a turf cladding was proposed, although not actually erected, the transversal timbers were left protruding rather further from the wall-faces than is usually in such reconstructions (illus 4). Additionally, it was felt that this external woodwork might diminish the difficulties associated with the initial firing of the timbers; and moreover, they made more of a visual impact for television viewers to whom the idea of a timber-laced wall might well have been an entirely unfamiliar concept. The writer feels that the exposed lengths of timber did not impair the validity of the experiment. The existence of such woodwork is, by its nature, not demonstrated archaeologically, but it is worth remarking that the ends of the transversal beams provided an excellent series of footholds which helped during the construction of the upper parts of the wall.

GENERAL CONSIDERATIONS ON THE CONSTRUCTION OF THE WALL

If it is accepted, as a working hypothesis, that vitrification is a by-product of the destruction, accidental or deliberate, of a timber-laced wall, it follows that such events are likely to have affected walls which were constructed some time previously, and which may thus have differed materially

ILLUS 4 Oblique view of the completed wall, showing the south-west face and the drystone construction of the north-west end

from the state of the East Tullos reconstruction. For example, the hearting may well have been subject to a degree of settling; and drying, and perhaps decay, could have altered the internal timberwork. Even disallowing the possibility of a turf or equivalent cladding, it is possible to argue that vegetation may have begun to establish itself in apertures in the wall-faces: vegetation was noted colonizing the upper part of the wall-face of the *murus gallicus* recently erected in the Bois de Boulogne, Paris, within two years of its building. Perhaps, continuing in this vein, it is legitimate to speculate further that later prehistoric warfare may have had a seasonal element to it, and that late summer or autumn may have been a favoured time for attempting to put the torch to such walls, when these structures may have been at their driest. Such speculative comment must be recognized for what it is, but such considerations may be borne in mind in relation to the course of events to be described below. It may be argued that setting fire to a pristine wall, built in the spring, and using timber which had been overwintered in the open in a builder's yard, less than adequately duplicates the most likely conditions that may be surmised to have prevailed when such walls were originally ignited. There were also periods of heavy rain during the building of the wall, both at the outset, when the materials were being assembled and, more critically, on the afternoon of 31 March, when building was being completed. This necessitated the postponement of the firing of the wall until the next day. It is, however, possible that wholly-dry materials would have hindered the onset of conditions suitable for vitrification – a consideration which will be treated more fully in due course.

A more specific objection which may be raised concerns the quantity of wood employed in the construction. It is this writer's impression that the proportion of wood, whilst perhaps marginally on the high side relative to the amount detectable on excavation in non-vitrified examples (a figure for the quantity of wood incorporated is frequently difficult to assess on the basis of the excavated data from such forts), is of the right order of magnitude. It is certainly lower than the proportion used at the Plean Colliery experiment. The quantity of wood may further be justified on account of the newness of the wall and, more importantly, the different burning properties of the pine that was used, rather than the oak which wood identifications suggest was the prevalent timber used in such walls, but which was understandably denied to us on the grounds of cost.

THE CONFLAGRATION

The original intention was to ignite brushwood piled against the middle of one of the long sides of the wall, such that a south-west or north-east breeze might assist in carrying the fire along the transversals into its core. In the event, the prevailing wind on the day the fire had to be ignited was from the north-west and was of the strength of a moderate to stiff breeze; this blew intermittently. Accordingly, the writer decided that the best plan would be to pile an articulated lorry-load of off-cuts of timber and brushwood along the south-west face of the wall, concentrating on the north-west sector, such that the breeze might fan the flames along the brushwood as well as into the wall by way of the transversal timbers.

Although we would have preferred not to have done so, we were prepared to use petrol to get the brushwood to ignite, since the actual lighting of this material did not form an essential component of the experiment; moreover, the brushwood had been soaked when an attempt was made to deliver it on the previous evening. Rather more controversial was the decision to smear the beam ends of the transversals with animal fat (in the form of dripping) to assist them to catch fire: this course of action was again determined by the downpour noted above. In all, some 10 lb (c 4·5 kg) of dripping were used, primarily on the beam-ends at the north-west end of the south-west face. As the north-west end of the north-east wall-face was subsequently set on fire successfully without recourse to any such artificial aids, it is clear that their use cannot be regarded as of critical significance. It may be stated categorically that there were no added materials in the core of the wall by way of chemical fluxing agents, brushwood, fuels or animal fats. Nor was refuse such as bone incorporated, although concentrations of Phosphorus pentoxide, noted in some analyses, have been taken to suggest that such debris may have been one of the constituents of the core (Youngblood *et al* 1978; Frederiksson *et al* 1983), the conclusion having been reached on the basis of the weight per cent pentoxide present in the vitrified glasses relative to that in the source rocks.

The brushwood fire at the north-west corner of the wall was ignited shortly after 12 noon on 1 April, at which time the thermocouples in the core of the wall were indicating a temperature of 1–3°C (illus 5). Somewhat contrary to expectations, the beam ends of the transversals ignited quite readily, and were well alight in the north-west sector of the south-west side within the first hour. By 13.00 hrs, smoke and steam were beginning to emerge in quantity from the north-east face of the wall and the wall-head (illus 6), and temperatures in the core began to rise slowly if steadily from 4°C at 13.00 hrs, to 14° at 14.20, 22° at 14.35, to reach 52°C some 20 minutes later. Unfortunately, this was to be the highest temperature recorded from the core of the wall for some considerable time. By this stage, the fire against the south-west wall-face was beginning to burn down (illus 7) and, whilst some of the visible beam ends were still alight, having burnt back level with the wall-face, those in the top row, no longer reached by the external fire, were either smouldering gently or appeared to be extinguished; the bottom horizon of beam-ends (and some of the second row) were still obscured behind the still-blazing debris of the brushwood fire. By 13.45 hrs, it was none the less clear that all the beam ends that had been attained by the brushwood fire had ignited successfully; furthermore the stonework of the wall-face was beginning to crack and bulge outwards. The heat radiating from the external wall-face was intense; it was measured at 750–800°C at 14.30 hrs.

ILLUS 5 Lighting the external fire of brushwood and timber off-cuts against the south-west side just after noon

ILLUS 6 Smoke and steam emerging from the wall-head, seen from above the south angle of the wall

ILLUS 7 Smoke and steam issuing from the south-east end wall as the initial external fire burns down. Time: approximately 14.00 hrs

By mid-afternoon, the breeze, which had been oscillating between north-west and west (when westerly, it was striking the major wall-face obliquely – the most advantageous wind we were to enjoy during the course of the experiment), finally settled in the north-west. This meant that it arrived end-on to our detached sector of walling. By 15.00 hrs, smoke and steam ceased to emerge from the rear of the wall in any quantity, and temperatures in the wall-core began to decline: 35°C was recorded at that time. Some of the transversal timbers were still on fire, and were continuing to burn in towards the hearting. Cold air was manifestly penetrating the wall in quantity. Our reactions were twofold. First, the crew continued to pile material on the brushwood fire against the south-west face: materials used included further scrap wood, as well as a miscellaneous cargo of domestic refuse, delivered by the City of Aberdeen Cleansing Department. Thus it was that old mattresses and a wardrobe were hurled into the blaze! The transversals continued to burn, or reignited successfully, and many were alight some 0·10 to 0·15 m behind the apertures of the beam-holes by this stage. Second, it seemed necessary to impede the airflow into the wall-core. At this juncture, it would not have been practical to erect turf cladding, as we had initially intended, and thus the writer decided to employ the best available substitute in the circumstances. This involved masking the exposed north-west end and the adjacent part of the north-east side with a tarpaulin. This treatment was markedly unsuccessful: the hearting temperature continued to fall, stabilizing in the low 20°C around 16.00 hrs. The writer then decided to remove the tarpaulin; the temperature in the wall-core continued to drop. At 17.00 hrs, five hours after the brushwood had been fired, the core temperature registered 13°C. After an equivalent timespan, the core of the Plean Colliery experimental wall is reported to have been a 'glowing red mass' (Childe & Thorneycroft 1938a, 49), the wall-faces having disintegrated two hours previously.

ILLUS 8 Removing partially-burnt debris of off-cuts from the wall-head; the tarpaulin has been removed from the north-west end, and lies folded at its base. Note that some of the facing stones display cracking

At about this time, the writer clambered on to the top of the wall. The earth and turf capping had baked slightly; smoke was emerging in small quantities from cracks in this surface (illus 8). A small hole was gouged out of this upper layer by hand to expose the small gabbros below; these proved to be only mildly warm to touch. Smoke was no longer appearing from the north-east face of the wall, despite the fact that the transversal beams in the opposite face were continuing to glow red and were burning back slowly into the wall-core. A thermocouple was inserted along one of these channels to a point about 0·3 m beyond the position at which the particular beam was burning: the temperature recorded, 79°C, was well below the range at which vitrification might be expected to occur. It was assumed that cold air was still penetrating the wall-core in sufficient quantities for low temperatures to be maintained. In a few cases, particularly in the uppermost row of transversals, where the timbers had burnt back beyond the beam-holes, small rubble had cascaded down, making further activity unlikely as the beam-channels were choked. Retrospectively, the employment of this small material, with its tendency to smother the fire, may be seen to have been a serious error.

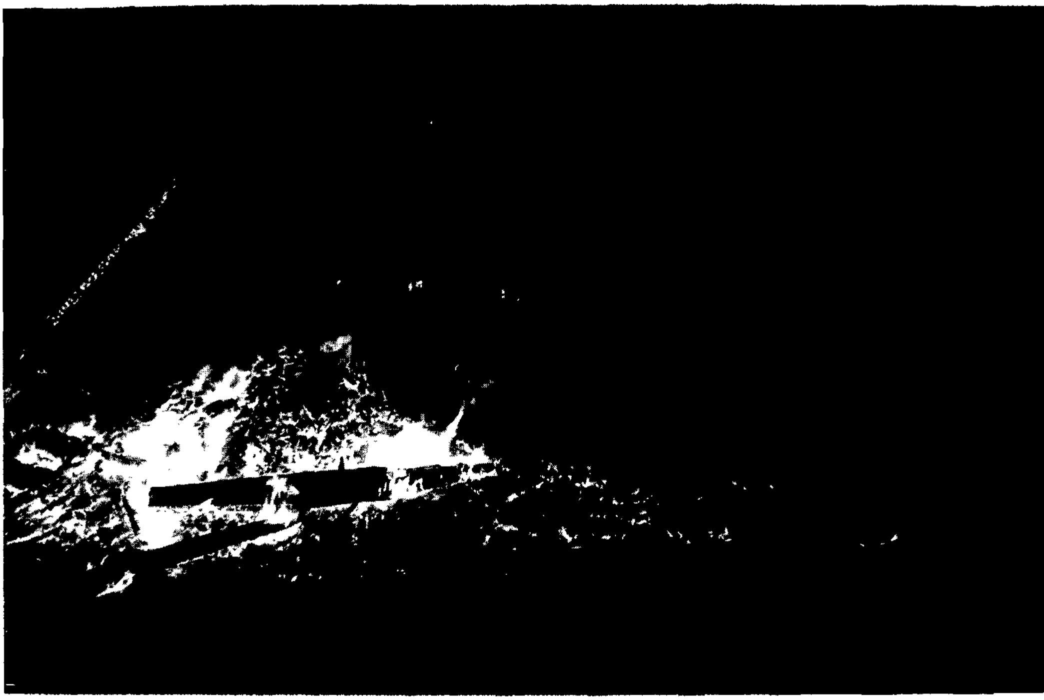
The arrival of a further lorry-load of stakes and off-cuts of timber about 17.15 hrs prompted a further change of plan. The wind remained north-westerly, and so the decision was taken to concentrate on augmenting the fire at the north-west end of the wall. The external fire was now focused on the north-west end of the south-west face, and was extended around the north-west end of the wall as far as the north-west beam-ends in the north-east face. In this way, it was hoped that the main flow of air into the wall which, on the basis of desultory smoke rising from the south-east end wall, was considered to be north-westerly, would be pre-heated before flowing into the wall-core. The fire was successfully led round the north-west end from the north-west end of the main south-west face, such that the transversal beam-ends at the north-west end of the north-east face were alight by 17.30 hrs. The smoke direction now showed that heated air was apparently being drawn into the wall-core from the fire ignited against the drystone-built north-west end of the wall. Despite this, an hour later the temperature of the core of the wall, as measured by the thermocouples, remained at what it had been at 17.00 hrs, although there was still intense heat emanating from the south-west wall face, where the majority of the beam ends were still alight.

The position at 18.30 hrs, after the fire had been alight for some six-and-a-half hours was thus as follows: the revetment stones of the south-west face showed extensive signs of cracking, and many of the beam-ends on that side were at least smouldering; the temperature in the hearting was however only just in double figures; and the north-westerly airflow meant that the external fire on the long sides was being drawn along the wall-faces, rather than directed towards the wall-core. The wall showed few signs of deterioration beyond those noted earlier – a slight bulging on the south-west side, and the localized blocking of some beam-channels by tumbled hearting. Temperatures in excess of 100°C had not been recorded, except on the south-west wall-face itself, and, with the north-west breeze still blowing, the possibility of producing vitrified material seemed as remote as ever. Rather in desperation, a final load of scrap timber was summoned.

This was delivered around 19.15 hrs, and consisted of much more substantial planks (up to 8·0 m long and 0·07 to 0·1 m thick) than had been the case previously. We hoped to keep the fire alight into the night with this material. By that time, there were two separate fires burning against the wall faces, one along most of the south-west side, and a second at the north-west end of the north-east face. The new supply was deployed at the north-west ends of the south-west and north-east faces; there was insufficient wood to re-kindle the fire against the footings of the north-west wall. By 20.00 hrs, all the timber had been put in position and was successfully alight. Flames leapt skyward from the conflagration on the south-west side, and the fire was also spreading along the beam-ends of the north-east side. Smoke began to billow from the south-east end, and from the neighbouring sector of the north-east side. A thermocouple inserted a little way into the stonework at the north-west end produced a reading of 190°C, but the temperature of the hearting had only recovered to 20°C before the batteries of the digital thermometer unfortunately failed. As will become clear, much higher temperatures must have been attained subsequently.

Between 20.30 and 21.15 hrs, as the bonfire against the north-west sector of the south-west face began to die back, various features could be noticed through the intense heat (illus 9). The stonework of the south-west wall-face at the upper limit of the flames was locally glowing red-hot. A few of the beam-ends in the middle two rows of transversals (about the fourth and fifth from the north-west end) exhibited signs of the fire being actively drawn into the core of the wall, here some distance from the position of the external fire. Elsewhere, most notably in the case of the southernmost timber in the bottom row of transversals, timbers which had been smouldering gently were now glowing red without having been re-kindled. On top of the wall, directly above the north-west sector of the south-west face, the occasional small flame could be seen. The impression we obtained from the intermittent character of these flames was that they were related to the burning of the upper part of the internal timber-lacing but, in the heat and the darkness, it is impossible to state categorically that these flames were not produced by the burning of debris from the external fire which had landed on the wall-head. The localized collapse of this part of the wall subsequently means that the writer remains unable to confirm this observation.

At 21.30, the remaining personnel temporarily left the site in order to eat. The wall had withstood four bonfires lit against it in the space of nine hours. Almost all the transversal beams had burnt back to the wall-face on the south-west side; and some were well alight some distance, perhaps 0·25 m, into the wall-core. The south-west face also showed some signs of settling and bulging;



ILLUS 9 The north-west end of the south-west face at approximately 21.15 hrs. Above the flames of the external fire, individual timbers can be seen burning in towards the hearting

individual stones therein were extensively heat-cracked and some of the granites seemed to be exfoliating. There had been no collapse of the wall-faces whatsoever.

Returning to the wall at 23.00 hrs the same evening, the position was as follows: on the north-east side, the external fire had almost burnt itself out, but some of the beam-ends of the transversals were still alight, although still forward of the beam apertures. On the south-west side, two distinct sectors could be seen to be glowing red. One was produced by the embers of the external fire at the north-west end; this still blanketed the bottom two rows of transversals. The other corresponded to the positions of various beam-channels, where the transversals had now burnt some distance into the core of the wall; these included the southernmost beam in the bottom row, remote from the later external fires. More spectacularly, the upper portion of the north-west end of the south-west face had collapsed on top of the embers of the external fire, bringing a small part of the hearting with it. Examination by torchlight did not reveal any signs of vitrification. The night was dry and by 23.00 hrs the wind seemed to have died away considerably; a light breeze from the west, as earlier in the afternoon, again blew.

The next morning was still dry; there had been no rain overnight. The wind had reverted to the north-west, but was no stronger than previously. No further collapse had taken place, and no more general settling of the wall material had ensued from the previous evening's fall (illus 10). The fire on the north-east side of the wall had been extinguished; this side displayed localized cracking of the facing stones and charred beam ends. Contrastingly, the beams on the south-west side, immediately to the south-east of the area that had collapsed, were still alight a considerable distance – approximately 1 m – back into the core of the wall (illus 11). The beams directly behind the tumbled sector of

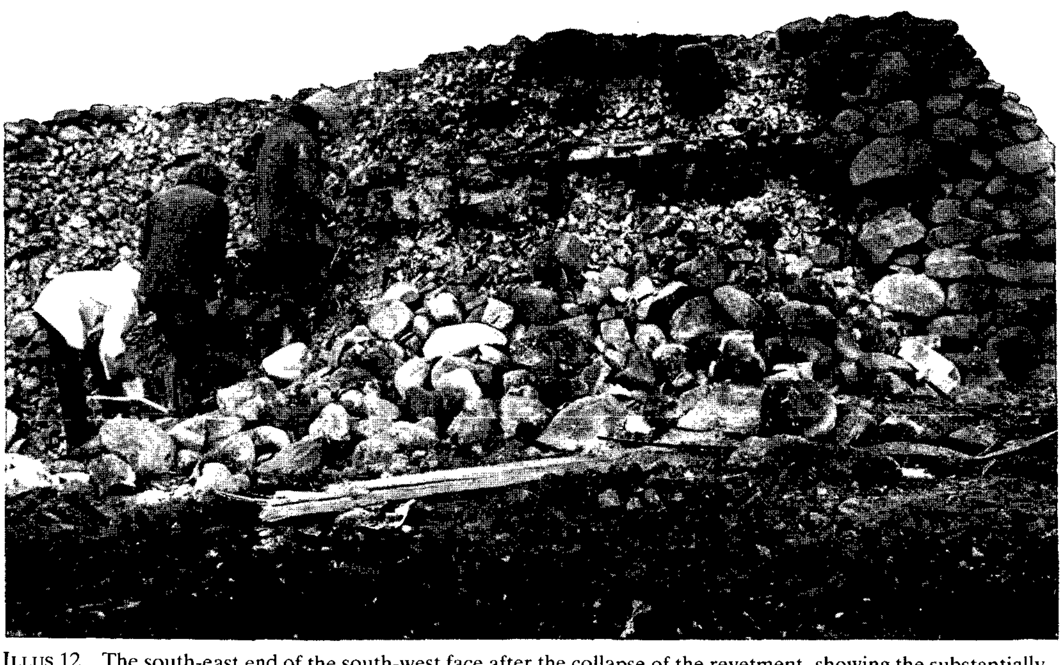
ILLUS 10 The south-west face at 08.30 hrs on 2 April

ILLUS 11 Detail of the wall-face adjacent to the collapsed section of the south-west face. Note the condition of the stonework, the beam still alight in the aperture, and the bent steel pipe – once used to insert the thermocouple

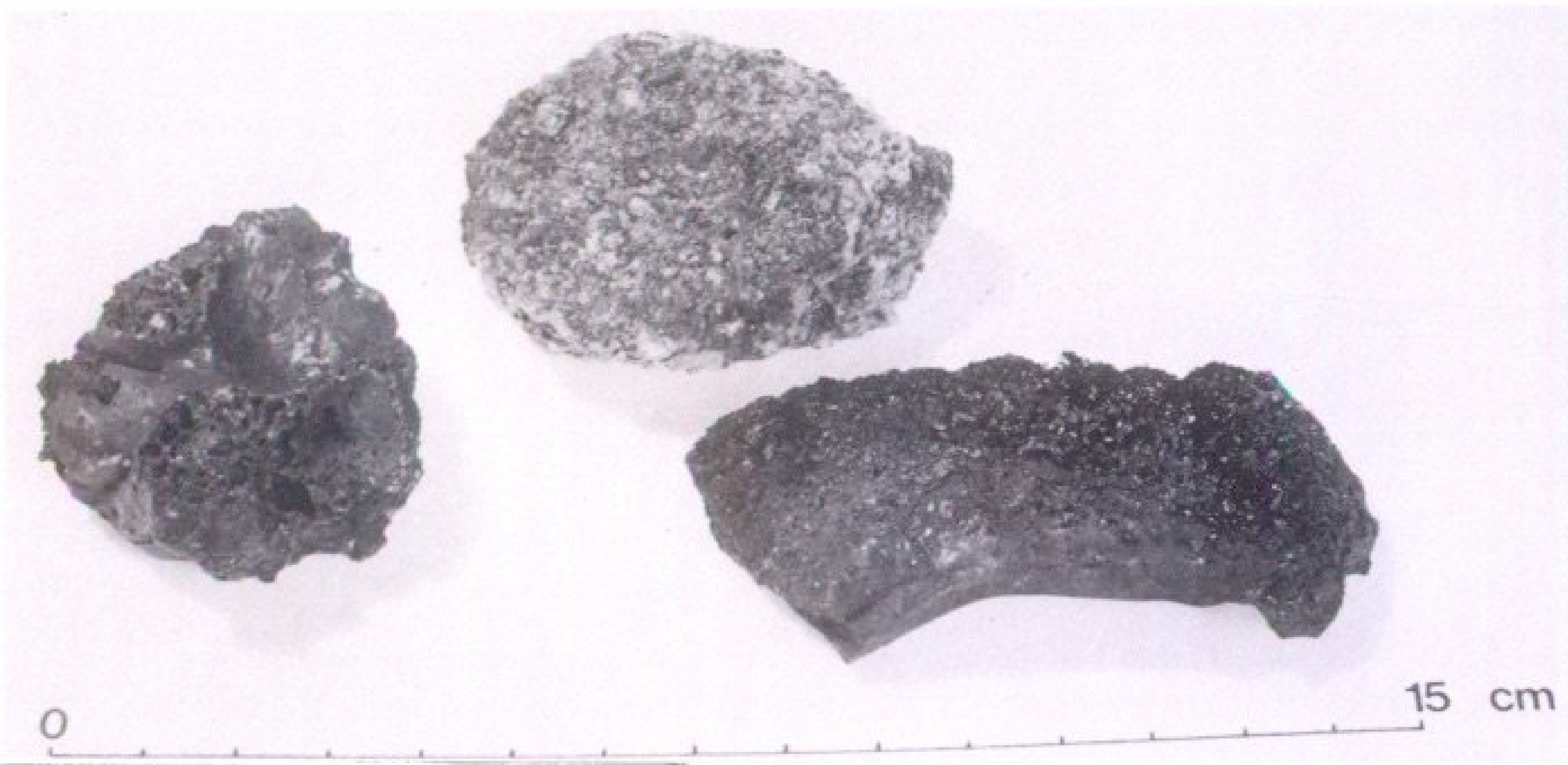
the wall could be seen to be still glowing red through chinks in the core material, and a small amount of smoke was emerging lazily from the top of the wall. The stonework at the south-east angle of the wall (remote from any of the positions of the external fires) was warm to the touch, and elsewhere the surface stonework was too hot to handle with comfort, despite low ambient air temperatures. There were no visible signs of vitrification.

At 10.00 hrs, some 22 hours after the first bonfire had been ignited, work began on the demolition of part of the wall adjacent to the collapse to see whether any vitrified material could be located before the departure of the television crew. The team began by attempting to remove the collapsed wall-face in the north-west sector, thereafter delving into the adjacent hearting by hand. Four points conspired to make such an approach impractical. Of these, the safety aspect was most important: as has been noted previously, the upper parts of the hearting contained substantial quantities of small stones, and these were acknowledged to be particularly prone to further slumping. A second factor was the heat of much of the stonework, which could only be removed with gloved hands and which was melting rubber-soled footwear; a third was the slowness of progress; and fourth was the proximity of timber elements which were still alight. Moreover, the small quantity of material that was removed by hand failed to produce any signs of vitrified rock – almost all the core material that had ended up near the surface looking singularly unaltered. Examination also revealed that the timber framework displayed signs of having moved: in particular, it was apparent in the restricted view that we had into the wall-core that localized settling had resulted in some longitudinal beams resting on the transversals and in direct contact with them, rather than supported above them as was the case when the wall was built.

The next plan was to dig into the north-west sector of the south-west face using the mechanical



ILLUS 12 The south-east end of the south-west face after the collapse of the revetment, showing the substantially-intact timber lacing

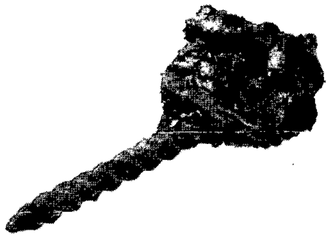


14

13

Illus 13–15 Examples of vitrified stonework recovered from the wall at East Tullos

15



ILLUS 16 Nail partially enveloped in vitrified material

shovel on a Drott caterpillar tractor. The material thus extracted from the wall was spread for the crew to check for signs of vitrification, while the author remained at the wall to supervise the extraction and to check for the presence of any substantial lumps of vitrified material. A small portion of the north-west core of the wall was removed by this means. In so doing, much of the south-west revetment of the wall, which had looked very unstable at 08.30 hrs, fell away, but the core materials behind it, retained by the timber lacing, remained substantially intact (illus 12). No substantial blocks of vitrified stonework were revealed *in situ*, but small pieces were recovered from the core of the wall, essentially from behind the temporary face of the exposed hearting towards the end of the wall, where, as has been remarked above, there were timbers still alight. These small pieces (illus 13–16) were noted amongst the material spread from the Drott's shovel, and came from approximately 1–1·2 m above the ground level, roughly the level of the second row of transversal timbers.

When several such pieces had been recovered, this procedure was stopped and final filming was completed. The wall was still smouldering, with the occasional visible timber still glowing red in the interior. There seems little doubt that the fire would have continued to burn for some considerable time; the writer would guess at least 24 hours, on the basis of the quantity of unburnt timber subsequently revealed. The structure appeared markedly unstable and Yorkshire TV, with filming schedules completed, was not prepared to accept the insurance risk represented by the wall any longer. Accordingly, at 16.00 hrs, some 28 hours after the experiment had started, the wall was bulldozed flat. Much of the internal timberwork, particularly at the south-east end of the wall, was intact, and limited burning of some of the timbers, particularly transversals, was still under way. Very few of the longitudinals, except those at the north-west end, had been burnt at all, and nowhere had fire travelled along a longitudinal to ignite, or even to scorch, a transversal, despite the fact that the longitudinals were parallel to the prevailing wind direction for much of the experiment. The scope for checking the bulldozed element of the wall for further examples of vitrified rock was obviously limited, but this was done as thoroughly as possible in the circumstances: none was noted.

THE OUTCOME OF THE EAST TULLOS EXPERIMENT

The amount (approximately 3 kg) of vitrified stonework produced as a result of this experiment is undoubtedly small, both in absolute terms and relative to the volume of the length of wall that was fired. Various factors have been mentioned above in mitigation: the newness of the wall; the continuing combustion at the time of demolition; the number of airholes offering ingress to cold air, with its quota of oxygen; the lack of hardwoods; and the dampness of many of the materials at the time of firing. The writer none the less feels justified in setting these results alongside those obtained by Childe and Thorneycroft (1938a) at Plean Colliery and Rahoy, and by Engström (1982) using limestones in Sweden, to support the refutation of the suggestion that the vitrified and calcined elements which have been noted in fortifications widely distributed across Europe could not have been produced as the result of the conflagration of varieties of timber-laced and timber-framed ramparts. There is, however, undeniably a major difference in the magnitude of vitrification products recovered from East Tullos and that represented at sites like Tap o' Noth. Whether the factors mentioned above are sufficient to account for this differential cannot be assessed by this author. It is important to emphasize that, of itself, the experiment offers no support to the continuing conjectures as to whether such alterations to the stonework of these walls was deliberately intended or not; and if deliberately intended, whether as a process of construction or destruction.

The experiment merely allows us to conclude that the burning of a timber-laced wall, without added fluxes (Frederiksson *et al* 1983), can produce the phenomena characteristic of vitrified stonework, including indications of timber casts. It should equally be stressed that it does not follow that all ramparts that display these features do so as a result of a sequence of destructive events akin to those outlined above. At one extreme, Nicolardot and his colleagues (1974, 44–5; Büchsenschütz 1984) have demonstrated that apparently 'calcined' material does not invariably imply the presence of heat in the range 900–1100°C that is proposed for vitrification (Frederiksson *et al* 1983, 165). Problems of potential misidentification, especially in older field observations, are perhaps more acute in calcined than in vitrified ramparts, and the calcined series should perhaps be set to one side here. Equally, it is not possible to use the results of this experiment *in vacuo* directly to refute the opposing case – that vitrification was an intentional constructional process, designed to strengthen these structures.

Examination in thin-section of the vitrified rocks produced experimentally suggests that they had been heated to a temperature of the order of 950°C (Prof I Parsons, pers comm). This result is consistent with temperatures in the range 1000–1100°C advocated as the solidus temperature for granite-based glasses from Scottish sites (Brothwell *et al* 1974, 105).

The location of the vitrified stones at the interface between the lower fill of large gabbros and the upper fill of smaller ones, combined with the observation that alteration was restricted to the smaller pieces, suggest that surface-to-volume ratios may be particularly critical with respect to limited vitrification of this kind. It may be surmised that the upper fill, packed with small stone, produced too restricted a circulation of gasses for vitrification to be successful. Against this, it must be remarked not only that steam and smoke were noted emerging from the wall-head but also that the small gabbros displayed a marked propensity to tumble into the beam-channels. Contrastingly, the larger material of the lower fill clearly differed in terms of surface-to-volume ratio, and may have contained too much airspace for the creation of the reducing conditions essential to the process of vitrification.

Small wood casts were noted on one of the pieces of vitrified stone, again duplicating a phenomenon noted in field observations. One of the nails incidentally incorporated in the wall was partially enveloped in vitrified material (illus 16), an observation which may offer support for the hypothesis that some vitrified forts may yet be shown to have contained nailed timber frameworks.

Rain occurred during both the Torsburg (Engström 1982) and East Tullos experiments; snow fell during the firing at Plean Colliery. The usual view, supported above, is that wet, or indeed rotten, timber-lacing would be inimical to the production of satisfactory results (Brothwell *et al* 1974, 103); Hogg has even contrasted the usual climatic picture, of increasing rainfall, proposed for the early Sub-Atlantic with the prevalence of sites north of the Forth–Clyde isthmus displaying indications of vitrification (1975, 62–3). However, it may be suggested that rainfall during the experiments was more critical for its effects in dousing the external fires and contributing to the lowering of temperatures on exposed surfaces than for any material difference it may have made to the moisture levels in the core. At Torsburg, a giant fan (Engström 1982, illus 6) was employed to simulate wind, which was lacking at the beginning of the experiment: this appears to have made little impact, and was switched off. Rain began to fall gently some 10 hours after the external fire had been lit, and subsequently became heavier; it was also accompanied by wind. The fire burnt-out after 24 hours.

The observation of steam issuing from the East Tullos wall is consistent with chemical analyses indicating low water contents for vitrified glasses from Scottish sites (Brothwell *et al* 1974, 104). Furthermore, Frederiksson *et al* (1983, 165) have suggested that the reducing conditions under which vitrification took place demonstrated analytically by Youngblood and her collaborators (1978) imply a 'confined, slow and oxygen-starved fire', in which direct distillation of the wood could produce methanol and other gasses with high ignition temperatures that could provoke localized vitrification. They also put forward the water-carbon reaction [$H_2O + C > CO + H_2 > CO + H_2 + O_2 > CO_2 + H_2O$ + energy] to account for the phenomena seen; and this would be consistent with the steam noted at East Tullos, and also at Plean Colliery. Sustained substantial water pressures would also lower the temperatures at which partial melting would occur (Frederiksson *et al* 1983, 169), but such conditions are unlikely to have pertained in the East Tullos wall, except very locally. The vitrified material that was recovered from the hearting did however appear at approximately the level at which the larger gabbros gave way to the smaller chips to which reference has already been made, and it is possible that mechanical settling of the core materials at this interface may have permitted water pressure to build up, if only to a limited extent.

At East Tullos, we did not incorporate any bone material or other refuse in the wall. It is therefore not possible to comment on the conclusion reached by Youngblood and collaborators (1978, table 1) that the high Phosphorus pentoxide content of certain glasses relative to the parent rocks of the ramparts whence they came is consistent with the presence of domestic rubbish or turf in the fabric of the wall. The use of such debris in later prehistoric fortifications is not unknown; on occasion, even when this would have weakened the structure, as at Crosskirk Broch, Caithness (Fairhurst 1984, 41–2). Bone was certainly recovered from Rahoy (Childe & Thorneycroft 1938b). Shells were incorporated in vitrified material recovered from Duntroon, Argyll and Bute District, but were not believed to have been a constituent of the wall (Christison *et al* 1905, 281); and shells were also recovered directly below a carbonized longitudinal beam in the inner face of the slightly-vitrified wall at the Green Castle, Portknockie, Moray District. We may provisionally conclude that observations of bone and shell have certainly as yet been too infrequent to postulate that such materials were regularly incorporated in the core, but that an admixture of such material – especially on sites with evidence of occupation prior to the construction of the wall – need occasion no surprise. An assessment of the volume of bone necessary to account for the observed Phosphorus pentoxide enrichment would clearly be of assistance. It is, however, possible that the proportion of Phosphorus pentoxide can be explained without recourse to the hypothetical addition of minor components of the kinds proposed above (D Sanderson, pers comm).

It has also been suggested to the author that the burning of apparently Potassium-rich woods (such as *Quercus*) might contribute to lowering the temperature at which the silica component of the parent rocks might melt (D Longley, *in litt*). Youngblood and co-workers' table 1 (1978, 103–4) does show that many, although by no means all, of the analysed glasses have enriched levels of potash relative to the parent rocks. Whilst these workers considered that the K_2O figures, like all except those for Phosphorus pentoxide, could be explained perfectly satisfactorily by partial melting (1978, 117), these analyses do not preclude potash having played a role in the system. If this hypothesis is sustainable, it would further account for the limited vitrification achieved using pine in the East Tullos experiment. However, it would seem that the role of potash as a fluxing agent – even with higher proportions of wood in the walls than was the case at East Tullos – can only have been marginal. Whilst potash may have been of slight significance in producing conditions favourable to vitrification in the immediate vicinity of the timbers themselves, it appears unlikely that this substance could have been present in anything like sufficient quantities to produce wider effects. On the whole, given the general absence of evidence for fluxes after a century of analytical effort, it is perhaps best to discount potash having played a role in the vitrification system.

Arguments against the constructional use of the techniques of vitrification derived from this experiment certainly appear strong to this author; but it has to be acknowledged that they are not incapable of being overturned. Clearly, such arguments have as much to do with the condition of the wall by 2 April as with the amount of altered stonework produced. For the constructional hypothesis to be sustainable, an experiment in which the techniques of vitrification were employed as part of the constructional process might be of assistance by demonstrating the feasibility of such an exercise: either vitrification could be attempted as, so to say, the terminal act of wall-construction, or stage by stage, as has been proposed for certain French sites exhibiting calcination: la Brèche-au-Diable in Calvados (Edeine 1966, 258–9) is a case in point. Déchelette (1913, 709, n 3), following de la Noë, documents the unsuccessful efforts of a French officer to vitrify the brick foundation for a gun-battery in 1782! No matter how such an experiment were to be conducted, it is important to stress that, as far as the Scottish field and excavation evidence is concerned (MacKie 1976), radical reinterpretation would still be required, perhaps even to the extent of proposing a function for vitrified walls other than defensive enclosure.

GENERAL CONSIDERATIONS

Points that may be advanced in favour of the destructive nature of vitrification can be put forward by juxtaposing the results of the trial with observations from excavation and fieldwork at other sites, as MacKie has done (1976). Even at well-preserved sites such as Tap o' Noth, Gordon District (Ralston *et al* 1983, pl 1), where there is little reason to suspect subsequent robbing, where individual vitrified blocks reach impressive dimensions, and where vitrified material is present around much of the circuit of the enclosure, the volume of unaltered stone which has tumbled from the rampart appears quantitatively greater. Clearly, the results of the East Tullos experiment offer almost a *reductio ad absurdum* in this regard, since the quantity of vitrified material produced was so meagre. Despite the problems which afflict the experimental results, it seems worthwhile stressing that the vitrified material was recovered, as predictable from field observations (Nisbet 1974, 6), from the core of the wall – and in that sector of it which showed the severest disintegration during the course of the conflagration. The unstable state of much of the structure at the end of the experiment has been outlined already; it seems entirely likely that fuller vitrification would have rendered the unvitrified portion of the wall even less stable. If this assumption is accepted, it seems a reasonable conjecture that the irregular patterns of vitrified blocks and less-altered stonework that is represented in the field by most of even the more-fully vitrified sites cannot ever have provided a serviceable defence without supplementation. To the limits of this author's knowledge, no excavated wall has yet produced evidence for a built second-phase defensive construction enveloping the vitrified material and broadly contemporary with the apparent date of the vitrification. This argument, since it is *ex silentio*, is admittedly weak; but the indications, at sites like Craig Phadrig, betoken refurbishment of the defences only after the passage of considerable time (Small & Cottam 1972). Elsewhere, as at the Camp des Chastres, Aubusson, Creuse, France, refurbishment was achieved by building over the burnt wall (Léger 1972), or by the selection of a new line.

Whilst the provisioning of most later prehistoric forts with water is unknowable, it seems reasonable to suggest with Nisbet (1982, 28) that extinguishing fires that had got hold either in lean-to structures built against the fortifications or in the fortifications themselves would have been difficult to achieve. It thus seems feasible for fire to have spread into the wall from fires accidentally started in adjacent buildings; however, the quantities of timber required to ignite the external face of the experimental wall suggest that destructive conflagrations provoking vitrification during the heat of battle would appear to have been difficult to arrange. Whilst the large quantities of material used in the external fires at the experimental wall may have been partially conditioned by circumstances at the time, including the wind direction, this factor might help to explicate Caesar's comment (*de Bello Gallico*, VII, 23) on the difficulty of burning such walls. It is therefore proposed that vitrified walls which show evidence of having been ignited from their external faces are more likely to indicate a controlled episode of destruction after the cessation of hostilities than an event that took place when fighting was actually in progress. All the indications, from scientific analyses to field experiments, are that getting the rampart timbers to ignite was not casually achieved. Dixon (1976, 165–6), for example, reports problems in setting fire to a replica built in Gloucestershire in 1970.

Furthermore, both Engström's work (1982) and the East Tullos experiment suggest that the times put forward by Childe on the basis of the results achieved at the scaled-down replicas built at Plean Colliery and Rahoy for vitrification to occur represent considerable underestimates for full-scale works. Indeed, neither the Torsburg nor the East Tullos walls were particularly thick: the former burned for 24 hours; and the latter was alight after 28 hours and still contained substantial quantities of timber. Its condition on the morning of 2 April strongly suggests that, had it been encouraged to burn longer, more extensive vitrification could have been provoked. Clearly, the duration of heating may have been significant to the extent of lowering the temperatures at which vitrification could have occurred. However, the writer suspects that this consideration is likely to have been of very limited significance, in so far as the temperature attained at any particular point in the wall may be considered to have been dominated by the proximity or otherwise of burning wood and charcoal.

Whether or not it is accepted that vitrification is a by-product of destruction by fire, there can be little doubt that enclosures which display widespread evidence of altered stonework demonstrate very considerable pyrotechnical abilities on the part of the fire-raisers. It may be not unreasonable to propose specialists – akin to the specialist builders of the post-Roman centuries discussed by Graham (1951, 65–74). Isotopic dates for the first millennium ad (Ralston 1980; Alcock 1987, fig 4), to set alongside those for the first millennium bc, make it abundantly clear that the ability to produce vitrification is not restricted to a narrow chronological band (*pace* Brothwell *et al* 1974). Whether the evidence from Scotland alone, or from Europe, is considered, instances of vitrification are almost coterminous with the extreme dates for the erection of timber-laced walls themselves. It is noteworthy that Graham's compilation of references to the destruction of sites includes several references to the use of fire, in some instances at least clearly after a site had been captured. The application of TL-dating to vitrified forts should increase the number of sites for which an element of absolute chronology is available (Sanderson *et al* 1985).

Finally, it is worth drawing attention to the matter of spectacle. The experimental wall at East Tullos, edged by flame and glowing red at night, made an impressive sight, even against the backdrop of a modern city. The progress of widespread vitrification around the 563 m-high summit of Tap o' Noth must have appeared awesome to the prehistoric communities of great tracts of the Garioch and neighbouring areas – a spectacular advertisement of power.

NOTE

The vitrified stone produced in this experiment has been deposited in the Anthropological Museum, University of Aberdeen.

ACKNOWLEDGEMENTS

The author's thanks are due to Yorkshire Television Ltd for proposing and financing the experiment, especially to Mr Simon Welfare, Producer of *Arthur C Clarke's Mysterious World*, and Mr Nick Lord, Researcher, who arranged the supply of the necessary materials. Permission to write up the experiment was granted by Mr Filip W Cieslik, Contracts Executive.

The building of the wall was efficiently achieved owing to the expertise of Messrs George Blackhall and Robin Callander and their crews. I am very grateful to them all. Moreover, both George Blackhall and Robin Callander provided useful data on the construction, and this information has been incorporated in the above report.

The site was made available by the City of Aberdeen District Council's Cleansing Department; the Department also provided the Drott machine used in the later part of the experiment.

I am indebted to Professor Ian Parsons and Dr Nigel Trewin, Department of Geology, University of Aberdeen, for organizing the thermocouples and for sectioning some of the vitrified stones that were produced.

For advice (some of it obtained by Mr Lord) received prior to, and since the experiment, I am grateful to Dr Olivier Büchsenschütz (CNRS-ERA-314, Paris), Professor Fred Glasser (Department of Chemistry, University of Aberdeen), Mr Peter Hill (Whithorn Trust), Professor Ray Kazmann (Emeritus Professor of Engineering, Louisiana State University, Baton Rouge), Miss Helen Nisbet (Lasswade), Dr David Sanderson (SURRC, East Kilbride) and Dr Elizabeth Youngblood (Geosciences Department, Arizona State University, Tucson). I am much obliged to Mr and Mrs Ian Keillar (Elgin) for translating parts of Engström's paper from the Swedish.

The photographs used for illus 2, 3, 5, 7, 8, and 12–16 were taken by Mr Jim Livingston, Department of Geography, University of Aberdeen; the remainder are by the author. All were printed at the Department of Archaeology, University of Edinburgh.

REFERENCES

Alcock, L 1987 'Pictish Studies: present and future', *in* Small 1987, 80–92.

Brothwell, D R, Bishop, A C & Woolley, A R 1974 'Vitrified forts in Scotland: a problem in interpretation and primitive technology', *J Archaeol Sci*, 1 (1974), 101–7.

Büchsenschütz, O E 1984 *Structures d'Habitats et Fortifications de l'Age du Fer en France septentrionale*. Paris. (=*Mémoires de la Société préhistorique française*, 18.)

Büchsenschütz, O E & Ralston, I B M 1981 'Les remparts des âges des métaux', *Archéologia* (Dijon), 154 (1981), 24–36.

Childe, V G & Thorneycroft, W 1938a 'The experimental production of the phenomena distinctive of vitrified forts', *Proc Soc Antiq Scot*, 72 (1937–8), 44–55.

Childe, V G & Thorneycroft, W 1938b 'The vitrified fort at Rahoy, Morvern, Argyll', *Proc Soc Antiq Scot*, 72 (1937–8), 23–43.

Christison, D, Anderson, J & Ross, T 1905 'Report on the Society's excavations of forts on the Poltalloch Estate, Argyll, in 1904–5', *Proc Soc Antiq Scot*, 39 (1904–5), 259–322.

Collis, J R & Ralston, I B M 1976 'Late la Tène defences', *Germania*, 54 (1976), 135–46.

Déchelette, J 1913 *Manuel d'Archéologie Préhistorique, Celtique et Gallo-Romaine*: Vol II, part 2 – *Premier Age du Fer*. Paris.

Dixon, P 1976 'Crickley Hill, 1969–72', *in* Harding 1976, 161–75.

Edeine, B 1966 'Le rempart de l'éperon barré de la Brèche-au-Diable (dit aussi du Mont-Joly) commune de Soumont-Saint-Quentin (Calvados)', *Gallia Préhistoire*, 9 (1966), 247–62.

Engström, J 1982 'Ett murexperiment på Gotland', *Tor*, 19 (1980–2) (1983), 53–75.

Fairhurst, H 1984 *Excavations at Crosskirk Broch, Caithness*. Edinburgh. (=*Soc Antiq Scot Monogr Ser*, 3.)

Frederiksson, K, Youngblood Anthony, E & Frederiksson, B J 1983 'The Celtic vitrified forts', *in* Kempe, D R C & Harvey, A P (eds), *The Petrology of Archaeological Artefacts*, Oxford, 154–70.

Graham, A 1951 'Archaeological gleanings from Dark Age records', *Proc Soc Antiq Scot*, 85 (1950–1), 64–91.

Greig, J C 1972 'Cullykhan', *Curr Archaeol*, 3 (1971–2), 227–31.

Harding, D W (ed) 1976 *Hillforts. Later Prehistoric Earthworks in Great Britain and Ireland*. London.

Hogg, A H A 1975 *A Guide to the Hill-forts of Britain*. London.

Léger, P 1972 'Le camp des Chastres, commune d'Aubusson: campagne de fouilles, 1972', *Mémoires de la Société des Sciences naturelles et archéologiques de la Creuse*, 38, 1 (1972), 35–9.

MacKie, E W 1969 'Timber-laced and vitrified walls in Iron Age forts: causes of vitrification', *Glasgow Archaeol J*, 1 (1969), 69–71.

MacKie, E W 1976 'The vitrified forts of Scotland', *in* Harding 1976, 205–35.

Nicolardot, J-P 1974 'Structures d'habitats de hauteur à caractères défensifs dans le Centre-Est de la France', *Antiquités Nationales*, 6 (1974), 32–45.

Nisbet, Helen C 1974 'A geological approach to vitrified forts, Part I', *Sci & Archaeol*, 12 (1974), 3–12.

Nisbet, Helen C 1975 'A geological approach to vitrified forts, Part II', *Sci & Archaeol*, 15 (1975), 3–16.

Nisbet, Helen C 1982 'Vitrification phenomena in hill-forts', *Readings Glass Hist*, 15–16 (1982), 21–30.

Ralston, I B M 1980 'The Green Castle and the promontory forts of North-East Scotland', *Scot Archaeol Forum*, 10 (1978) (1980), 27–40.

Ralston, I B M 1981 'The use of timber in hill-fort defences in France', *in* Guilbert, G (ed), *Hill-Fort Studies: essays for AHA Hogg*, Leicester, 78–104.

Ralston, I B M 1987 'Portknockie: promontory forts and Pictish settlement in the North-East', *in* Small 1987, 15–26.

Ralston, I B M, Sabine, K A & Watt, W G 1983 'Later prehistoric settlement in North-East Scotland: a preliminary assessment', *in* Chapman, J C & Mytum, H C (eds), *Settlement in North Britain 1000 BC–AD 1000*, Oxford, 149–73. (=*Brit Archaeol Rep*, 118.)

Sanderson, D C W, Placido, F & Tate, J O 1985 'Scottish vitrified forts: background and potential for TL dating', *Nucl Tracts*, 10 (1985), 799–809.

Small, A & Cottam, M B 1972 *Craig Phadraig. Interim report on 1971 excavation.* Dundee. (=*Occas Pap, Dept Geography, University of Dundee*, 1.)

Small, A (ed) 1987 *The Picts. A new look at old problems*. Dundee.

Youngblood, E, Frederiksson, B J, Kraut, F & Frederiksson, K 1978 'Celtic vitrified forts: implications of a chemical petrological study of glasses and source rocks', *J Archaeol Sci*, 5 (1978), 99–121.