A GEOLOGICAL APPROACH TO THE STUDY OF MEDIEVAL BRICKS

by

Ronald John Firman and Patricia Eleanor Firman

Summary

Medieval bricks from East Anglia, Lincolnshire and the Midlands have been examined using standard geological techniques. The petrography, colour, surface and internal structure provide evidence of the sources of raw material and methods of manufacture. The significance of the geographical distribution of medieval brick is discussed in relation to the distribution of superficial deposits. The problem of dating bricks is explored.

Introduction

The history of English medieval brickwork has been discussed in detail by Nathanial Lloyd (1925) and Salzman (1952) has collated the documentary evidence. Lloyd's review was so comprehensive that no-one has attempted to do more than add detail to this classic work. Nevertheless in at least three respects Lloyd's book is incomplete. Firstly, his list of medieval brick buildings is by no means complete; secondly, he made no study of the texture, structure and mineralogy of the bricks themselves; and thirdly, no attempt was made to explore the probable sources of brick clay used. Furthermore the various methods of manufacture were only partly discussed.

It was with these points in mind that we began research into medieval brick two years ago. Our map showing the distribution of medieval brick in East Anglia when superimposed on a geological map of the superficial deposits, suggests that there might be a close correlation between the type of brick and local geology (Fig. 2) This working hypothesis has been largely confirmed by field-work in this and other regions but we have not yet looked at any brickwork south of the Thames. The purpose of this paper is to discuss the criteria which may be used to establish the probable source and method of manufacture of bricks, where documentary evidence is lacking. Furthermore, it is hoped that this paper will stimulate the interest of geologists in this much neglected field of study.

There are no published contemporary descriptions of English medieval brick making. Reference has to be made to contemporary literature from the Continent and to later English writings. The earliest of these English descriptions (quoted by Nathanial Lloyd, 1925) is from the late seventeenth century. There are also several descriptions from the eighteenth century (also quoted by Nathanial Lloyd). The current practices of the nineteenth century are discussed in the comprehensive account of Dobson (1882).

His descriptions are so close to the earlier English and Continental ones, that we conclude that the industry remained conservative for a long period. Probably similar methods were in use in the Middle Ages. In the brickyard at Hull, working between 1303 and 1433, the accounts show that the materials and equipment were similar to those used at a later date (Brooks 1939). Consideration of the documentary evidence available enables us to give a generalised description of the probable method of manufacture of moulded bricks in the Middle Ages.

The selected clay was dug in autumn and piled in heaps to allow frost action to break it down. In Spring it was tempered, i.e. trodden or turned with spades to produce an even consistency. The resultant clay was then moulded in wooden moulds. The brickmaker worked at a table, first sanding or wetting the mould, then throwing into it a lump of prepared clay. Surplus clay was sliced from the top of the mould with a wooden stick (the strike) or a cutting wire on a bow.

The moulded brick was then carried (sometimes in the mould, sometimes on a small board, or ("pallet") to the drying ground, which was previously strewn with hay, straw or sand. The raw bricks were laid out in a herringbone pattern and when the first row was partly dry, a second was laid across the first and so on, up to ten rows high. This pile of drying bricks was commonly called a "hack". Straw or covers protected the hack from rain and sun until dry enough to burn. This usually took about a month.

Burning took place in kilns or clamps (the terms were apparently interchangeable) the structure of which is not well known. We do know, however, that the kilns were made from unfired bricks if fired bricks were not available and that inside, the bricks were often stacked as in the hack.

Accounts of the period tell of the fuels used. Wood was a common fuel and at Hull they used turf. Coal was used in the seventeenth century and could have been in use earlier.

The documents available relate to moulded bricks. We have some evidence that other methods of shaping clay for firing as bricks were used during the Middle Ages.

From the geological standpoint bricks may be regarded as sedimentary rocks which have suffered cataclastic and plastic deformation during digging, tempering and moulding, followed by thermal metamorphism in a kiln or a clamp. Therefore, bricks may be studied using geological techniques similar to those which are applied to thermally metamorphosed sediments. Although the temperatures achieved in a kiln are often higher than in natural metamorphism, the temperature is maintained for a much shorter time and the reactions take place at atmospheric pressures. Consequently equilibrium is less often reached and more of the original sedimentary textures are preserved in bricks than is usual in naturally metamorphosed sedimentary rocks. Original clastic constituents and fossils can often be distinguished.

Original Clastic Constituents

(i) Stony inclusions In many medieval bricks stony inclusions are common and are usually virtually unaltered. Occasionally, flints have been observed which have cracked as a result of quick cooling of the fired brick. Colour changes may also result from heating, but, in the great majority of bricks, the stony inclusions, in shape, size and colour look identical to their sedimentary counterparts (Plate 9).

The stony inclusions, therefore, may be assumed to be similar to those in the original brick clay or brick earth, since stones would certainly not have been added. Because most of these stony inclusions expand slightly on heating, whereas the surrounding clay may shrink, serious cracks in the brick might be expected; but, in spite of the large number of medieval bricks which have stony inclusions, cracked bricks are rare. Considerable skill must have been exercised in choosing stony clays which would not crack when burnt or, alternatively, there may have been many failures.

Since stony inclusions are so common, and since they represent the virtually unaltered stones of the brick clay, or brick earth, they ought to be useful in proving the source of the raw material. Unfortunately by far the commonest stony inclusions are small angular flints and rounded quartzites, which merely reflect the widespread distribution of such fragments in the glacial drift and alluvium deposits of Eastern and Central England. Claims that such inclusions prove the local nature of the brick clay (see for example Curzon's account of Tattershall Castle) are usually based on ignorance of just how widespread such stony clays are in England. The inclusions in bricks in Tattershall Castle (Lincolnshire), Kirby Muxloe Castle (Leicestershire), Buckden Palace (Hunts), Layer Marney Church (Essex) to cite but four examples, are virtually the same; yet there is no reason to believe that they were all made from the same brick-earth: it is far more likely that they were made from a variety of local brick-earths which happened to outcrop near these buildings. In a few instances, such as at Bradgate House, (Leics), where Charnian inclusions occur, some of the stony inclusions are sufficiently diagnostic for a strictly local origin to be assigned to them. Usually stony inclusions merely prove that the bricks were made from superficial deposits.

(ii) Clastic constituents in the matrix Like the stony inclusions, grains of quartz and felspar remain unaltered in the matrix. They may thus be directly compared with their sedimentary counterparts. As in unaltered sedimentary rocks the grain size and shape are important criteria in determining the mode of formation of the sediment. Such studies are possible on bricks only if samples can be taken and studied microscopically. We have not examined sufficient slides to draw any firm conclusions but the earliest bricks seem to have the more fine grained matrices.

Fossils from the original sediments

In bricks two sorts of fossils commonly occur. The first group consists of fossils which were present in the original sediment and not destroyed during brick manufacture: and the second group results from material added to or imprinted upon the brick clay.

A. D. Davis (1951) in a short note has described a Kimmeridgian assemblage in pottery from Oxfordshire but we know of no other record from fired clay. Davis remarks on the excellent preservation - "the shells, with their encrusting minute objects are unaltered after their service as an aggregate in potters clay". He suggests that the pots were only partly fired; but the same excellent preservation is seen in the well burnt Roman brick from Epperstone and in most medieval bricks containing calcareous shells. In the Epperstone (Notts) tile (Plate 10) a fragment of *Dactylioceras* was incorporated in the brick. The cast, in particular, illustrates the good preservation. Such preservation is perhaps to be expected in thick shelled creatures such as the ammonite cited above and, for example, the *Ostrea* seen in brickwork at Theddlethorpe All Saints (Lincolnshire); but thin-walled calcareous shells are often equally well preserved. Freshwater gasteropods, including *Planorbis* and *Bythnia* are abundant in the brickwork of the sixteenth century North Porches of the churches at Crostwick and Hardwick (Norfolk). Most of the details of the growth lines and ornament are preserved in these very thin-walled shells. Only the impossibility of extracting either the shells from the brick or the bricks from the brickwork, has prevented adequate study. Similar freshwater shells occur in post-glacial lacustrin clays, which were used for brickmaking at Icklington (Suffolk) during the nineteenth century. Undoubtedly the bricks of Crostwick and Hardwick were made from similar clays. The local freshwater deposits will be examined to see if they have the same shell assemblage as the bricks.

In the above examples the shells themselves are often preserved. Often, however, only the cast remains, as for example in a cockle shell impression in a brick in Cow Tower at Norwich.

Fossils are rare in bricks with stony inclusions but often occur bricks made from fine grained material. This undoubtedly is related to the comparative rarity of fossils in stony boulder clay.

PLATE 9

Fig. A. Brick cut to illustrate the angular flints and coarse porous texture. Tower-on-the-Moor, Lincolnshire (fifteenth century).

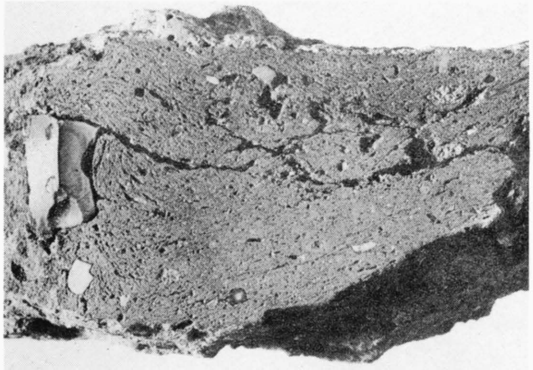
Fig. B. Another view of the Tower-on-the-Moor brick to show a rounded quartzite.

Fig. C. Cut surface of a modern Keuper Marl Brick. Note the pale angular cataclastic fragments derived from skerry sandstone bands and the dark rounded inclusions from more ferruginous laminae in the Keuper Marl. Structures in this brick are due to the mechanical crushing, mixing and extrusion of the Keuper Marl. These cataclastic structures contrast markedly with the plastic deformation seen in most medieval bricks.

Fig. D. Cut surface of half of a Caistor Castle brick (Norfolk c. 1440). This brick has been overburnt and consequently the yellowish sandy laminae show up in marked contrast to the blue black of the rest of the brick. The structures appear to be the result of plastic deformation of sedimentary bedding during moulding. Note how, in the left hand corner, the structures conform to the shape of the brick mould. The clay here is less compacted than in the centre of the brick. Evidence that the surplus clay was struck from the top of the mould can be seen at the top left of the photograph. The brick was further distorted on drying and burning.

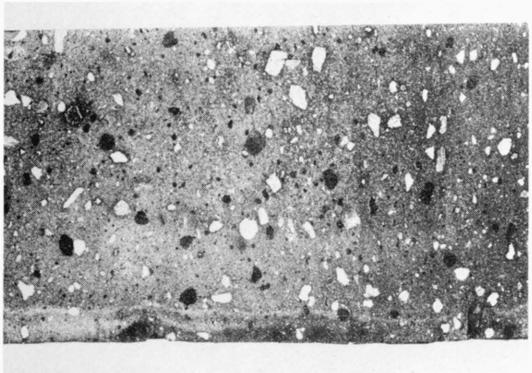
Fig. E. Part of a twelfth century brick from Little Coggleshall (Essex). Note the wide black core and the coarse sand contrasting with the fine grained matrix. Note also the sharp junction between the black core and the oxidised margin.

Fig. F. Part of a fourteenth century brick from Stanway, All Saints (Essex). Note that in contrast to the Little Coggleshall brick the black core is narrower and the margins more diffuse.

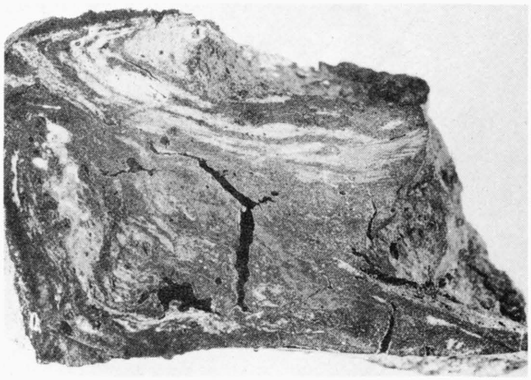


A

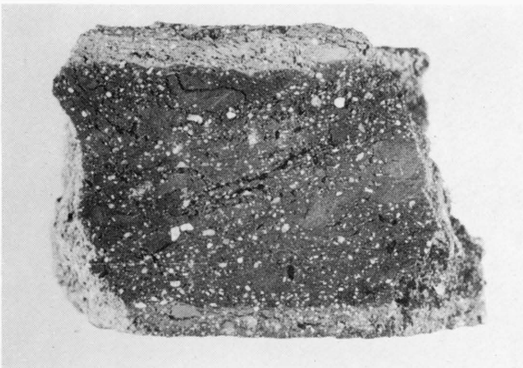
B



C



D



E

F

10cm.

Where bricks have been made from fossiliferous sediments, most of the fossils are preserved intact in the bricks. No doubt a more thorough search for fossils, particularly microfossils, would reveal many more in medieval bricks, which would be useful in determining the origin of the raw materials used in brick manufacturing.

Sedimentary structures preserved in medieval bricks

No structures which can be unambiguously ascribed to primary sedimentary structures have been found in medieval bricks. Probably such structures were either destroyed or severely distorted when the brick earth was tempered and moulded. It is, unlikely that any undeformed sedimentary structures exist in medieval bricks.

Structural changes induced during brick manufacture

By analogy with metamorphic rocks, bricks may be regarded as having suffered deformation prior to thermal metamorphism. This deformation is the cummulative result of the preparation of the raw material before firing: the brittle components are cataclastically deformed and the plastic material is plastically deformed. Cataclastic and plastic deformation structures thus commonly occur together in bricks as a result of the digging, tempering and moulding. All these processes in the Middle Ages, as in the nineteenth century (see for example Dobson , 1882), were aimed at producing a plastic clay suitable for moulding. Therefore it is not surprising that evidence of plastic deformation has been found in almost all medieval bricks examined.

(i) Cataclastic Structures These structures are best demonstrated by studying modern bricks where it can be proved that inclusions are due to deformation of the brick clay during brickmaking. For example the modern red brick made from Keuper Marl (Plate 9 Fig. C) has many small pale yellowish inclusions. Similar inclusions are absent from the original marl but are present in the brick before it is fired. They result from mixing the marl prior to firing. Examination of the quarry shows that these inclusions are likely to be derived partly from the skerry bands and partly from the softer green marl beds. The more brittle skerries have produced angular fragments and the softer beds more rounded inclusions both of which are yellow when fired. The proportion of these light coloured cognate inclusions is a measure of their original proportions in the Keuper Marl and their shape and size is a testimony to the character of the rock and the thoroughness of mixing. A few, well rounded, fine grained, dark red inclusions suggest that soft iron rich laminae in the marl were disrupted during mixing. In addition the alignment of the inclusions shown in Plate is the result of the method of extruding the marl.

Had the source of the brick clay not been known, information about the original sediment and its subsequent deformation could only have been deduced if it was assumed that the fabric of the brick was the result of mixing and extruding the marl and not due to cataclastic alteration of the marl by sedimentary processes. In studying medieval bricks no such assumption is justified unless it can be proved that the source material was undistorted prior to its use for making bricks. Many medieval bricks were made from boulder clays, which are likely to have been thoroughly mixed by glacial action before they were used for brick making. Thus, although abundant cognate inclusions similar to those in the modern Keuper Marl bricks commonly occur in medieval bricks, they are likely to be as much the result of the mixing of clays during the Ice Age, as during the Middle Ages.

Cognate inclusions, similar to those in the Keuper Marl brick, do however occur in bricks made from material other than boulder clay; and in these instances the cataclastic structures in the bricks are likely to be solely due to deformation during brick making.

None of the cognate inclusions in medieval bricks is as angular as those in the Keuper Marl brick, suggesting that the materials were more plastic than either the skerries or green marl in the local Keuper.

(ii) Plastic Deformation The cognate inclusions of medieval bricks are often plastically deformed, thus providing further evidence of the great plasticity of the raw material used in the Middle Ages. Often it is impossible to prove either when or how this deformation occurred. However, the structures often seem to be caused during moulding. Plate illustrates structures in a Caistor Castle brick (c.1440) due firstly to the pressing of a laminated clay into amould and secondly to the cleaning off of the top layer of clay, with a strike,plane or similar traditional brick makers tool (Dobson 1882). In this example the brick was evidently turned upside down on to straw; straw impressions are plentiful on the top surface. Any marks which might have been left when the excess clay was struck off the top of the mould have been obliterated by the straw impressions.

Surface markings made during moulding

Striae along the length of the top surface of bricks commonly occur. These are caused by the movement of a strike in removing the excess clay from the top of the mould. Similar marks, sometimes bifurcating downwards, are common on the sides of bricks. These are directed vertically and were fromed by gritty particles scouring the sides of the raw brick when it was tipped out of the mould. The under surface may be pit-marked where the suction of the brick clay within the mould has caused some of the clay to be torn from the base of the brick.

Surface marks caused by the moulding process are not always present in the finished brick: after all, the object of moulding was to produce as smooth a finish as possible. Nevertheless, surface markings are sufficiently common and sufficiently diverse to suggest that a variety of techniques were used.

Distortion during drying

To prevent the raw bricks sticking, drying floors were usually strewn with straw, hay or sand. Impressions of the straw and hay are commonly found on the undersides of the bricks. In medieval brick-work such impressions can be detected only when the brick can be removed from the brickwork and the underside examined. The bricks, when nearly dry, were often turned on their sides. In these instances a few straw impressions can be seen on the sides of the finished bricks. These bricks were made from very plastic clay which took a long time to dry out. Examples of such bricks have been observed in fourteenth, fifteenth and sixteenth century brickwork, for example at Cow Tower, Norwich; Caistor Castle and Crostwick Church (near Norwich). Straw marks are, however, commonest in early medieval brickwork; although, surprisingly enough, they were not observed at Little Coggeshall, Essex, where the earliest English medieval brickwork occurs.

When raw bricks are laid on a sanded drying floor, sand grains adhere to the brick. This sand is, however, difficult to distinguish either from sand from the mould or the moulding table or from sand sprinkled on the bricks during drying.

Bricks were occasionally stacked in a hack before they had properly dried. This resulted in the impression of the upper brick being superimposed on the brick below. Such impressions are quite often seen on only just a few of the stretchers in medieval brickwork(e.g. Feering Church porch, Essex) since only a few bricks in any one batch would be likely to be incompletely dried when put into a hack. The east wall of Bishop Alcock's Palace, Ely, is exceptional in that almost all the stretchers have impressions on them; clearly almost all these bricks must have been plastic when put into the hack. Consideration of the orientation of these hack impressions shows that, in all the examples seen to date, bricks were laid on their sides at about 30^{o}–45^{o} to each other. This is consistent with the herring-bone arrangement described in 1683 (quoted by Lloyd, 1925, p.34).

Added Materials

In the majority of cases so far examined, little indication of material added during the digging and turning of the raw material has been found. Judging by Victorian practice, the most likely additives would be inert material such as sand, fluxes such as straw or ground chalk or fuel such as coal dust or cinders ("breeze").

(i) Sand The Little Coggeshall (Essex) brick (Fig. E Plate 9) has abundant angular grains of quartz and flint, averaging about 1mm. in diameter, evenly distributed throughout a very fine-grained matrix. The lack of intermediate-sized grains suggests that this is an artificial mixture. If this deduction is correct, then as early as the twelfth century some brick-makers were aware of the value of adding sand to plastic clay to reduce the shrinkage on drying and burning. This technique was already known and used by potters in East Anglia. One of the outstanding characteristics of Little Coggeshall bricks is the precision with which they have been moulded and their lack of subsequent distortion. The original mixture could not have been very wet since the bricks do not show any straw marks: if they were laid out on straw to dry they were certainly not plastic enough to stick to the straw. Specially fine-grained mixes were apparently used for the more intricately moulded bricks (see Gardner, 1957, for details of moulding). The bricks at Little Coggeshall appear to be unique in their method of manufacture and in the sophistication of their moulding technique for such an early date.

In Tudor times elaborate mouldings were achieved by using specially selected materials. For less elaborate mouldings, stony boulder clays, with a sandy matrix, were used. These natural mixtures of sand and clay, like the apparently artificial mixture at Little Coggeshall, did not shrink unduly when burnt.

(ii) Fluxes In Victorian times, straw or ground chalk were occasionally added to brick clays (Dobson, 1882) and chalk is still added in making London Stock bricks. These ingredients have two distinct functions; they reduce the shrinkage on drying and lower the vitrification temperature. If too much chalk is present, as in the Gault, the vitrification range is reduced (Bonnell and Butterworth, 1950), making distortion on burning more likely if the kiln temperatures cannot be controlled within narrow limits. The addition of chalk to brick earth is therefore a matter of keeping a balance between adding enough to minimise shrinkage on drying and yet not adding so much that firing becomes difficult. If the chalk is not finely ground, free lime may form which, on hydration, may violently disrupt the brick. Moreover, the presence of lime in brick clays results in pale pinks and yellows on burning. The addition of chalk is, therefore, a highly skilled operation.

Many early bricks, such as at Little Wenham (c.1280) Cow Tower, Norwich (1380) and Caistor Castle (c.1440), have yellowish-orange and greenish-yellow hues which, coupled with high colour values and high saturation, seem to indicate high lime/iron ratios. Regretably, few chemical analyses of medieval bricks have been attempted: those quoted in Table I are the first published analyses known to the authors. These analyses do not show abnormally high lime contents when compared with ranges of 0-26% in modern bricks (Butterworth, 1953). In spite of the fact that many thirteenth, fourteenth and early fifteenth century bricks have colours suggestive of high lime content, there is no evidence that this was due to the deliberate addition of ground chalk. But more detailed chemical studies of both early medieval bricks and the probable source clays is necessary before a firm opinion can be expressed.

Most straw impressions are confined to the surfaces of bricks. Occasionally straw impressions occur within the brick itself, as at Hussey Tower (Boston, Lincolnshire) and in a few examples at Caistor Castle (Norfolk). So rare are these examples that the writers believe that these are accidental rather than deliberate examples of the incorporation of straw.

Provisionally, therefore, we suggest that no fluxes were deliberately added in medieval times to brick earth or brick clays. We also suggest that the yellowish colours of some early bricks were due to the use of natural clays with a fairly high lime content and not due to additives. The almost total lack of similarly coloured Tudor bricks we believe was due to the deliberate rejection of clays and brick earth which were not red burning. Further research on the chemistry of medieval bricks in recommended.

(iii) Fuel The technique of adding either coal dust, cinder or ashers to assist burning is certainly of some antiquity. Thus, for example, an act of George II allows the sale of "Bricks made of real Brick Earth wherein may be mixed any quantity of Sea Coal Ashes, sifted or screened through a Sieve or Screen half an inch wide" (quoted by Lloyd 1925 p. 49). Coal dust was found by Mayes (1965) in medieval brick Kiln at Boston and was considered by him to have been added to the brick clay during manufacture. Nevertheless in the authors' experience both carbonaceous inclusions and cinders are exceedingly rare in medieval bricks. All of the black specks observed in the field have turned out on closer inspection to be iron hydroxides and the only authenticated case of cinder inclusions is at Crostwick (Norfolk). The practice of adding fuel to the brick clay does not appear to have been common in the Middle Ages. Similarly we have seen no evidence that grog (calcined shale, broken tile etc.) was added.

Possibly additives were not used until high quality brick-earths and brick clays became scarce. Certainly by 1725 the practice of adding great quantities of "soil called Spanish" was sufficiently common practice in the vicinity of London to be discussed in an Act of Parliament.

Results of firing.

The general rarity of evidence of excessive distortion due to too rapid drying and the remarkable lack of contraction cracks in most of the bricks made from stony clays combine to suggest that the medieval brick-makers were well aware of the importance of care during drying and during the early stages of burning. On the other hand we have little information about wastage and only the best quality medieval bricks remain today. The wide range of colours in many thirteenth, fourteenth and early fifteenth century brick buildings may in part be due to lack of adequate temperature control in kilns and clamps. This, coupled with the higher temperatures required for the non-calcareous stony clays favoured in the mid to late fifteenth and sixteenth centuries, points to the widespread use of coal as a fuel in place of wood faggots at this period. However, the contrast in colour and texture betweend the bricks of the early and late Middle Ages may be as much a reflection of the choice of raw materials as of techniques of firing. The following generalisations seem to apply to all the brickwork so far examined by the authors.

(i) Black cores These are not an uncommon feature of early medieval bricks. They have not been recorded in Lincolnshire, Yorkshire or the Midland Counties (South East England has not been explored). Inasmuch as their distribution is localised, with a particular concentration in East Anglia it might be argued that the raw material controls their incidence. Conversely, the lack of black-cores in almost all fifteenth and sixteenth century bricks suggests improved techniques. Nevertheless, black cores are produced in some modern bricks, particularly when the raw material is rich in organic matter or pyrites.

Essentially, black-cores result from the lack of oxidation of ferrous compounds in the centre of the brick. This is often due to the presence of sulphur compounds or carbon (Searle and Grimshaw 1959, p. 284 and p. 290) in the raw material. They may be avoided by raising the burning temperature only slowly and by ensuring a free circulation of air (op. cit., p. 659). Too dense a mixture, too rapid drying and too rapid burning all tend to prevent the free circulation of oxygen through the bricks, so that only the outer part is oxidised. Black-cores are so common in Roman bricks and tiles that it seems certain that the technique rather than the raw material was the prime cause.

Early medieval bricks, such as the black cored bricks from Little Coggeshall and Stanway (Plate 9 Fig. f) have very fine grained matrices which show evidence of considerable compaction. Thus the commonest of black cores in medieval East Anglian bricks (made prior to about 1440) seem to result from the preference for fine grained silts (probably rich in organic matter) which were probably strongly compacted and too quickly burnt. Later in the fifteenth and sixteenth centuries, when sandier brick earths were preferred, black-cores become less common; they still occurred, however, wherever strong clays rich in organic matter were used.

Black cores are not, as is sometimes suggested, the result of "underbaking"; quite often black-cored bricks have been vitrified. Where temperatures have been too low a brown easily weathered core results, as at Polstead (Suffolk).

(ii) Colour Brick colours are the result of a subtle interplay of the concentrations, particle size, shape and distribution of the chemical compounds and glasses which form on firing. The colour or colours of the resulting bricks depend partly on the initial composition and texture of the raw material and partly on firing conditions. As demonstrated by Seger (1902), iron compounds are principally responsible for the colours in bricks. The ratios of iron to alumina, lime and magnesia determine the general colour (i.e. hue) and the percentage of iron determines its intensity (i.e. value) resulting under oxidising conditions in colours ranging from whites, creams and orange to red. With high firing temperatures these colours become darker and more saturated (i.e. value and chroma change).

Medieval bricks have been described using a standard "Munsell Color Chart" in terms of hue, value and chroma. In most medieval buildings it has been possible to record the range of colours from the least burnt to the most overburnt bricks. This demonstrated that the great majority of dateable late fifteenth and sixteenth century bricks exhibit a very narrow range of hues compared with earlier bricks (Fig. 1). Since these ranges include both overburnt and underburnt samples, the greater range in earlier bricks cannot be due to fluctuations in firing conditions but must be due to variations in the composition of the raw materials. This variation is illustrated by the chemical analyses of Caistor Castle bricks (Table 1) which show quite striking variations in Al_2O_3 and CaO. The lime to ferric iron ratio seems to determine the colour. It seems that, prior to about 1440, brick makers were more concerned with the texture of the brick clay than the resulting colours.

TABLE 1 Chemical analyses of Caistor Castle bricks (c. 1440)

	Yellow Wt. %	Red Wt. %	Overburnt brick Wt. %
SiO_2	65.67	59.13	64.50
Al_2O_3	12.03	15.87	11.21
Fe_2O_3	6.15	6.84	6.71
FeO	0.99	0.99	1.12
MgO	2.77	2.65	2.77
CaO	7.00	4.53	5.45
Na_2O	0.99	0.62	0.77
K_2O	2.02	2.60	2.47
TiO_2	0.70	0.72	0.84
MnO	0.06	0.07	0.08
P_2O_5	0.38	0.35	0.27
Loss on ignition	1.43	6.04	4.21
	100.19	100.41	100.40

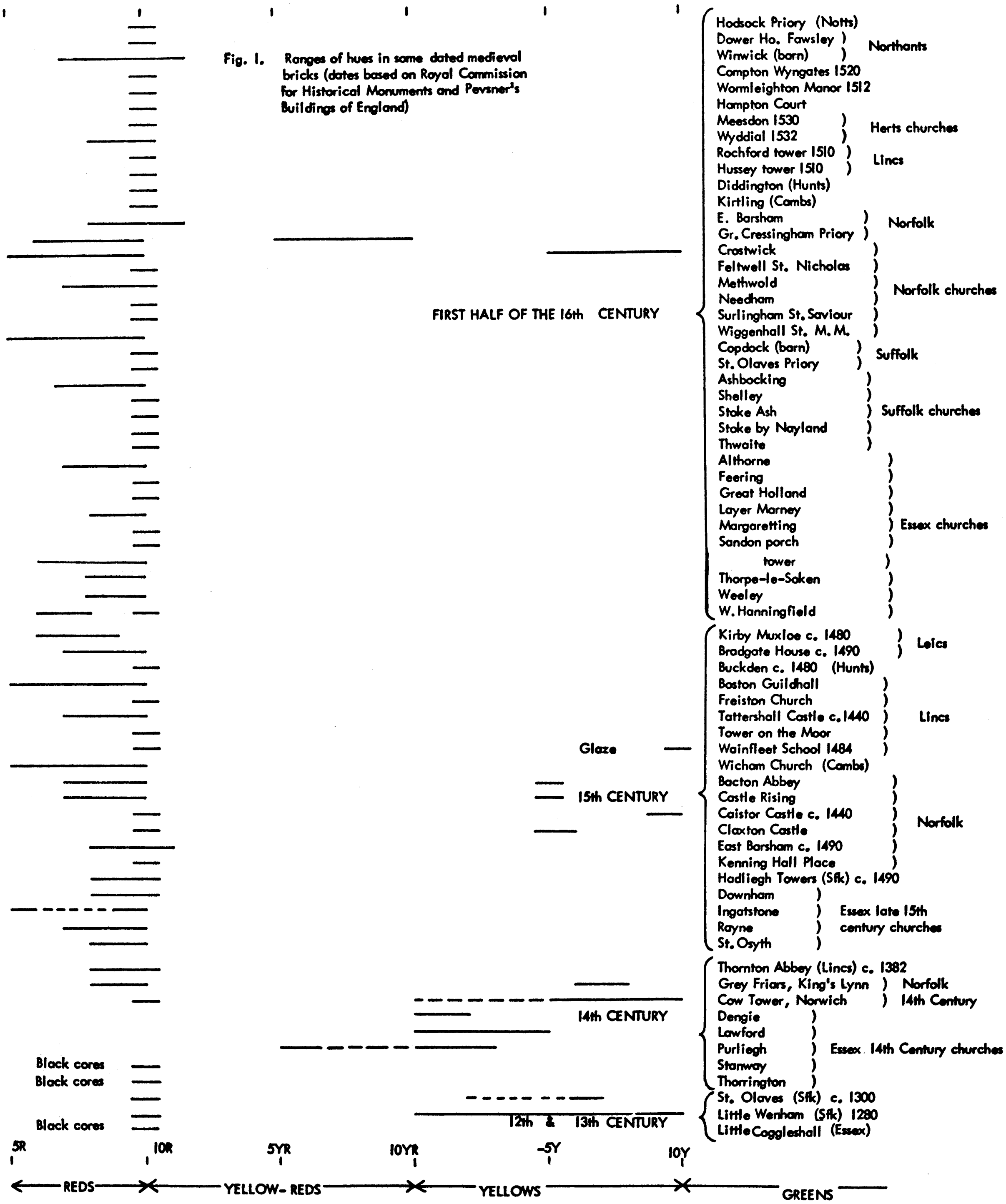


Fig. 1. Ranges of hues in some dated medieval bricks (dates based on Royal Commission for Historical Monuments and Pevsner's Buildings of England)

After 1440 brick makers became more colour conscious and did not choose clay which would produce a wide range of colours when burnt. Apart from Hengrave Hall, 1540 (Suffolk), where creamy bricks were used, the only brick earths burnt in any quantity were those whose hue on burning was between moderate red and moderate reddish brown (5R – 10R on the Munsell Color Scale). On vitrification these hues do not change, although the colours become more saturated. The most common brick colour – moderate reddish brown (10R 4/6) – becomes darker and more saturated, leading to a dark reddish brown (10R 3/4). No matter how high a temperature is reached during firing, yellow bricks cannot be made from these clays. In contrast many of the clays used before 1440 gave reddish brown when underburnt, which changed through yellowish-orange, yellows and greenish-yellow before they vitrified. Similar bricks were produced in the late fifteenth and early sixteenth century but only in small quantities where red burning clays were not available. They were not used in the major buildings of the period.

(iii) Vitrification The prevalence of yellowish bricks before 1440 strongly suggests that the clays used had a high lime-ferric iron ratio. The ease with which many of them have vitrified and distorted suggests a high absolute lime content. Many of these yellow or greenish-yellow bricks are vitrified at one end whilst the other end is reddish brown. Similarly, even where vitrification has not occurred, a single brick may exhibit a range of colours not confined to the surface (e.g. Cow Tower, Norwich c. 1380).

Furthermore, where vitrification does occur, blistering is common. All these observations suggest that not only did the clays vitrify easily but their vitrification range was small. This meant that, since the temperatures in the kilns could not be closely controlled, uniform and undistorted vitrified bricks could not be produced from the clays then currently used.

One of the achievements of the late fifteenth and sixteenth century brickmakers was that they discovered brick earths which would not only produce consistent red colours but could be vitrified in a controlled manner without serious loss of shape. These raw materials were mostly decalcified silty boulder clays and alluvium, both usually containing angular flint and rounded quartzite pebbles. Where, as in the Fens, this material was not available, diaper work was not attempted. Thus the several brick church towers, porches, clerestories and secular buildings in Kings Lynn, Boston and the Fens (which in Essex would have had much diaper work) are plain and although they burn red, they tend to distort when they are vitrified. Only one attempt to use such clays for diaper work has been seen by the authors. This is at Wainfleet (Lincolnshire) and is quite unlike any other diaper work in this country; the vitrified bricks are badly misshapen and have a light olive (10Y 5/4) glaze which contrasts markedly with the moderate reddish brown bricks (10R 4/6) of the rest of the building. It is interesting to note that Bishop Waynfleet had an elaborately diapered tower constructed at Farnham (Surrey): and it may well have been at his insistence that diaper work was attempted with such unsuitable materials at Wainfleet.

Two misconceptions about vitrified bricks and diaper work are deeply entrenched in the literature. Often it is suggested that vitrified headers were merely the bricks which happened to be overburnt. The evidence, however, suggests that they were prepared with the express intention of producing vitrification; often only one end is glazed and it appears that this was dipped in sand prior to firing. Perhaps occasionally vitrified headers were produced accidently, but in the majority of cases their production was planned.

The second common misconception concerns the supposed subtle fading out of diaper patterns (Lloyd 1925 p. 68). Examination of many examples has convinced us that this is often the result of subsequent weathering; the present appearance of many diaper patterns is quite unlike their original form, since much of the glaze has weathered off. This is particularly true of those bricks which were only partly vitrified and which, under the glaze, are indistinguishable from the majority of bricks in the building. In this respect medieval bricks used for diapers are quite unlike their Victorian counterparts of bluish tinge produced in a reducing atmosphere; these latter do not change their appearance on weathering but, since they are of a different hue, they do not blend so harmoniously as do the medieval examples.

PLATE 10

Fig. A. Hay impressions on the underside of a sixteenth century brick from Crostwick, Norfolk. Some of the holes on this surface are gasteropod impressions.

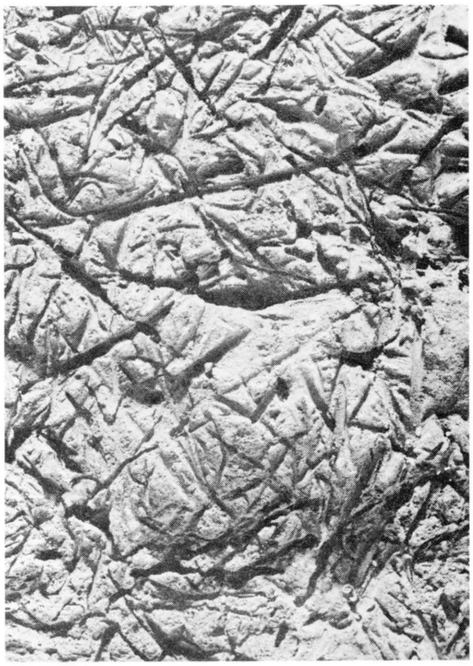
Fig. B. Straw impressions on the underside of a brick from Surlingham, Norfolk.

Fig. C. Ammonite fragments preserved in a Roman tile from Epperstone, Nottinghamshire (presented by Mr. Robert Alvery).

Fig. D. Cut surface of the Surlingham (Norfolk) brick illustrating the variable nature and plasticity of the brick earth.

A

10cm.



B

C

D

Post-metamorphic changes

After bricks are removed from the kilns or clamps, a number of alterations in their physical form and chemistry may occur as a result of the bricks adjusting themselves to equilibrium at the lower temperatures. The principal changes are expansion, due to incorporation of water from the atmosphere, and effluorescence. By analogy with metamorphic rocks, these changes may be classified as post-metamorphic changes.

Expansion is usually slight and complete after a few days. In exceptional circumstances, however, the linear expansion may be serious and may continue for two or three years. In modern conditions, using dense mortars and close joints, this may cause serious structural failure in brickwork particularly if the bricks are used straight from the kiln. In medieval conditions, however, the use of soft lime mortars and wide joints would prevent subsequent damage to brickwork. Consequently no estimate of the probable expansions of medieval bricks can be attempted.

This expansion is due to the slow infiltration of water. Where this is accompanied by hydration of quick lime the expansion may be rapid and explosive. Free lime is likely to occur in bricks vitrified from chalky boulder clay and must have been one of the hazards encountered by medieval brick makers. Some of the badly cracked overburnt bricks may be due to this hydration but without detailed examination of the bricks this is difficult to prove.

Effluorescence is a fairly common feature of Victorian and modern brickwork, but it is rare in medieval brickwork. It is due to the evaporation, at the brick surface, of water containing soluble salts such as magnesium sulphate. The source of these soluble salts may be either from the soil beneath the brickwork, from the morar, or from the bricks themselves. The extreme rarity in medieval brickwork of any effluorescence attributable to the bricks themselves is further evidence that only the weathered top few feet of superficial deposits were used: such deposits are likely to have been well leached before they were dug and bricks made from them would be unlikely to suffer from effluorescence.

It must be remembered, however, that only the best quality medieval bricks remain in external brickwork. Although those which remain are a tribute to the skill of the medieval brick maker, many less-well-made bricks must have weathered away.

Discussion

One of the principal results of a geological approach to the study of medieval brick has been the demonstration that deductions may be made about the character and source of the raw materials and about the methods of manufacture quite independent of the documentary evidence. Such conclusions may then be compared with the historical evidence, with a view to clarifying current opinions about the history of English brick making. This approach involves detailed studies of the lithology, structure and petrology of bricks, together with studies of the character and distribution of potential source materials.

A serious drawback is the lack of adequate geological information and maps. Often it has been possible to establish that particular bricks were made from boulder-clay and then to find that it is not possible to establish which boulder-clay was used, since the characteristics of the local boulder clays have not been sufficiently particularised or since drift maps are not available. In the Midlands many superficial deposits which were probably used for brick-making have been omitted from the published maps. A formidable amount of detailed research would have to be undertaken to prove (if indeed it is provable) that a particular brick was made from sediments from a particular brick pit.

In spite of these difficulties it is possible to draw broad conclusions about the source materials and methods of manufacture of medieval bricks, about the distribution of medieval brick buildings and the dating of bricks. These supplement and modify current opinions. We would stress, however, that since our researches are incomplete these are interim conclusions which, strictly speaking, apply only to those buildings (all north of the Thames) which we have personally examined.

(i) Source materials All the evidence of plasticity, fossils and inclusions suggests that only superficial deposits were used. Carboniferous Shales, Keuper Marl and Jurassic Clays, from which 80% of our bricks are now made, were definitely not used at all. This accounts for the strikingly different appearance of medieval buildings in areas where more recent bricks have been made from these older sediments. Thus for example, the Elizabethan Hough End Hall (Manchester) brick contrasts with the Carboniferous bricks of South Manchester; Kirby Muxloe Castle, Bradgate House and Edwalton Church tower contrast with the Keuper Marl bricks of South Nottinghamshire and Leicestershire; and, most startlingly of all, the red brick of Bishop Alcock's Palace contrasts with the dominantly yellow brick of most of Ely. Such contrasts in texture and colour between medieval and, for example, Victorian brickwork usually indicate the abandonment of superficial deposits in favour of older sediments. In much of East Anglia, however, superficial deposits continue to be used today and medieval brick in some areas differ from later brick more in shape and size than in colour and texture.

Since we have not looked at all the brick buildings built on or near Cretaceous and Tertiary clays it is possible that these sediments may have been used during the Middle Ages. The Historic Monuments Commission has suggested that Gault (Cretaceous) was used in Cambridge, but we doubt this and think it more likely that lime-rich superficial clays were used. In Essex the extensive outcrop of the London Clay (Eocene) suggests that it was likely to have been used, but we have no evidence of this.

In most instances it is not possible to identify accurately the type of superficial deposit. However, it is always possible to arrange the sources into one of two groups depending on whether they contain stony inclusions or not.

The stoneless group includes river, estuarine, lacustrine and fen silts. Only where fossils have been identified has it been possible to distinguish between these facies. Almost all bricks earlier than 1440 (Tattershall Castle) examined by the authors have been the stoneless type, but J.S. Gardner (personal communication) states that fourteenth century tiles at Pleshy Castle (Essex) are stony. The sandy inclusions we have seen in early bricks are consistent in size and grading with fine river gravels (e.g. St. Nicholas chapel, Little Coggeshall), the largest fragments being flints 3-4 millimetres in diameter; at Little Coggeshall these are set in a very fine matrix.

Where other materials were not available, fine grained silts continued to be used throughout the Middle Ages and at least to the end of the nineteenth century. After about the middle of the fifteenth century red burning clays were preferred those which gave varigated colours.

The bricks made from stony brick earths are typically characterised by rounded quartzite pebbles and angular flints (often 2-3 cm. in diameter) and sandy matrices distinctly coarser than the stoneless types. They appear to be either pebbly boulder clays or silty terrace gravels derived from the boulder clay. The rarity of yellowish bricks suggests that usually only the decalcified boulder clays were used. So far it has not been possible to correlate these bricks with particular glacial or alluvium deposits but, as with the stoneless silts, their distribution, with very few exceptions, is entirely consistent with the known distribution of the most probable source material. In almost all cases the nearest available source material has been used.

(ii) Methods of manufacture The geological approach provides no information about the digging of brick clays. Nor does it yield any evidence of the methods of preparing and tempering the clay. Detailed examination of the structure, texture, shape and surfaces of bricks does, however, provide abundant information about moulding and drying techniques; these have been adequately discussed in earlier sections of this paper.

All the information presented so far relates to moulded bricks and the impression may have been gained that only moulding techniques were used. However, some bricks vary so considerably in size that moulds cannot have been used. For instance, measurements of bricks in Cow Tower (c. 1380) at Norwich gave a range of lengths from 8 $\frac{3}{4}$ to 12 inches and widths from 4 to 6$\frac{3}{4}$ inches. Most likely such bricks were chopped up after being trodden out on straw.

The earliest bricks (from Little Coggeshall) were moulded and it seems probable that both techniques were used throughout the Middle Ages, the choice of techniques depending principally on the plasticity and water content of the sediments. The heavier, stickier clays could not be moulded and the drier stony silts could not be chopped up, hence techniques were partly dictated by the characteristics of the available material. No doubt the personal preference and experience of the brick maker would be an important factor.

Although neither technique died out, changing styles of architecture demanded precisely shaped bricks so that by the mid-fifteenth century almost all bricks were moulded. The type of moulding was governed by the plasticity of the raw material and its firing characteristics. Where, as in the sixteenth century church porch at Hardwick (Norfolk), the clay was not amenable to intricate moulding since it tended to warp when burnt, the bricks had to be cut after firing. Probably the distinction between "slop moulding" and "pallet moulding" made by Dobson (1882) may have been true in the Middle Ages. The essential difference is that, whereas with slop moulding the moulds were wetted, with pallet moulding the moulds were sanded. Slop moulded bricks had to be laid out on straw or hay to dry, whereas pallet moulded ones could often be placed directly into a hack. Since the principal distinction is whether or not sand was used for moulding, we prefer to substitute the term "sand moulded" for "pallet moulded". As mentioned earlier, sand moulded bricks may be difficult to distinguish from slop moulded bricks which were later sanded to aid drying. After the mid fifteenth century, with the increasing use of sandy boulder clays, sand moulding became the dominant technique.

As far as can be established sand, straw, chalk or cinder was not commonly added to brick clays in the medieval period. Isolated examples suggest that these techniques were known, even if not extensively practised in the Middle Ages. It is difficult to ascertain which fuel was used and whether kilns or clamps were used on a particular site. It is unlikely that the detailed study of bricks will throw much light on these problems: an evaluation of the documentary and archaeological evidence is required. Undoubtedly clamps fired with wood faggots were made at least until the late nineteenth century, so that it may be assumed that this method was used throughout the Middle Ages. Mayes (1966) has excavated a medieval brick kiln at Boston in which coal dust was used either for mixing with the brick clay, as Mayes suggests ; or for packing between the bricks prior to firing. No doubt the choice of kiln or clamp would depend on the size of the job; and the choice of fuel on the cost and availability. Possibly the need for closer control of firing conditions, necessary to produce the best Tudor moulded and vitrified brick, demanded kilns and coal or possibly charcoal for fuel.

This study therefore adds little to knowledge of the methods of manufacture, other than by establishing criteria which may be used to distinguish between the different ways of preparing and drying bricks prior to firing. Also we wish to emphasise that the characteristics of the sediments available was an important factor in deciding the methods used. As architectural demands, available sources of raw materials, and personal tastes changed, so did the method of manufacture; but probably no one method was exclusively used at any one time.

(iii) <u>Geographical distribution of medieval brick buildings</u> The general facts of the distribution of medieval brick buildings are well known. The great majority lie east of the Jurassic Oolites and, of these, most are in Essex, Suffolk and Norfolk. The two problems connected with their distribution concern the predominence of brick buildings in Eastern England and the reasons for the uneven distribution therein. The former problem has often been discussed, the latter in contrast has been ignored.

Among the reasons put forward for the concentration in Eastern England are the influence of Flanders and Flemish settlers, ideas brought back after wars with France or trade with the Hanseatic League; and the lack of alternative building materials. It is not the purpose of this paper to evaluate historical arguments but rather to discuss geological factors; therefore, only the last suggestion is discussed here.

Undoubtedly it is true that there is a dearth of freestone in Eastern England; silicified layers in the lower chalk (such as the Melbourne rock) are of limited use for exterior work. Nevertheless there is an abundance of flint in the Middle and Upper Chalk and there is a long East Anglian tradition of building in this intractable material. In Lincolnshire the Greensand, in spite of its poor weathering qualities, was extensively used. In south east England, Kentish rag and Wealden sandstone were important building stones. Moreover in all these areas, due to the proximity of the chalk and of an abundance of sand and gravel, there was no shortage of lime mortar to make good the deficiencies of flint, carstone, septarian nodules and other awkward building stones.

There were, therefore, stone alternatives to brick in eastern and south eastern England. Areas such as parts of the Cheshire plains, Midland England and the Vale of York and Herefordshire are perhaps no better endowed with freestone and yet few brick houses and no churches with brick are known to have been built in the Middle Ages. Nevertheless the argument based on the lack of fire resistant and durable alternatives to brick is a strong one which, when considered in conjunction with probable Continental influences, may adequately explain the concentration of brick in Eastern England.

There are, however, other geological facts which need to be considered. Since only superficial deposits were used it cannot be argued that the presence of younger, more workable clays (e.g. London Clay) in eastern England is an important factor. Suitable Pleistocene and Recent sediments such as boulder clay, alluvial "brick-earth", head and river silts occur in much of lowland Britain. As expressed by Clifton Taylor (1962), "in many cases it was not the clay but the will, and probably also the skill to make use of it which were lacking".

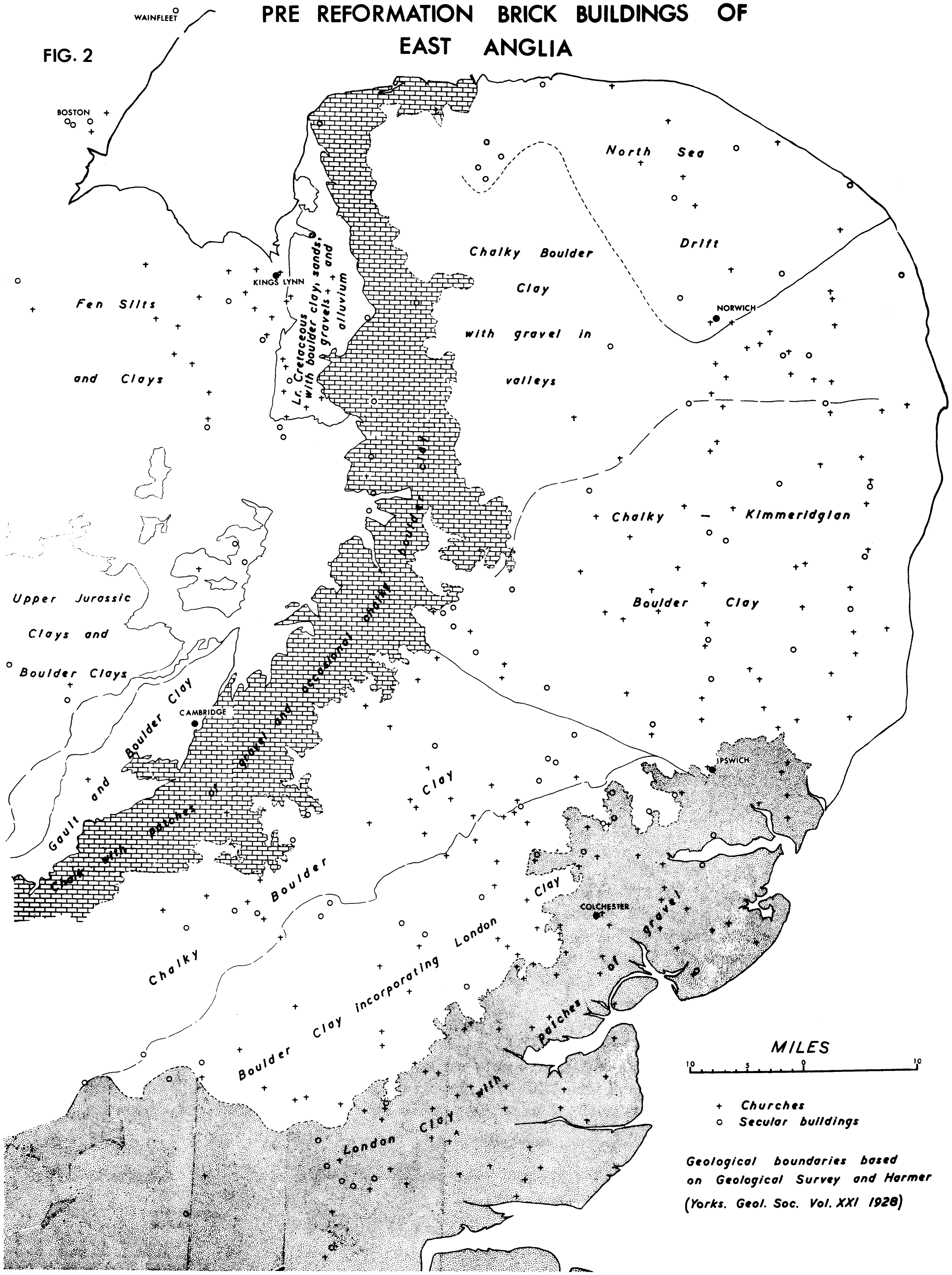
Nevertheless some individuals were determined to build in brick even in areas where freestone was easily obtainable. Thus the Chancery, Minster Yard, Lincoln (late 15th century) is sited very near an abundant source of freestone. Similarly Compton Wynyates (1520) and Wormleighton Hall (1512) in Warwickshire, Winwick House (16th century) and the Dower House at Fawsley (early 16th century) in Northamptonshire, are all near to good building stones. This deliberate choice of brick in areas west of of the stone-belt is not as rare as is commonly supposed. At least two dozen such buildings are known to the authors. All but four of these houses are within the area formerly covered by the Great Eastern Glacier which deposited boulder clay containing angular flints and quartzites. The bricks made from these boulder clays are thus indistinguishable from the bulk of the Tudor bricks of East Anglia.

Less than 1% of medieval brick buildings lie outside the provenance of flint; and so common is flint in late fifteenth and sixteenth century bricks that it is tempting to believe that the presence of small flints in the top soil was regarded as indicative of the likely presence of suitable brick earths. Even where flints are rare in the bricks, as at the Dower House, Fawsley (Northants), they are abundant on the ground. We still lack details of the distribution of medieval brick in the west Midlands, but our present data suggests that the coincidence between the distribution of brick houses built before 1540 and the distribution of flint in the boulder clays and alluvium is too striking to be fortuitous.

The uneven distribution within East Anglia can in part be explained by considering the availability of brick-clays and brick earths within the area. Thus, for example, there are no medieval brick buildings on the Chalk outcrop in Norfolk and Suffolk. (Fig. 2). Only where the chalk is obscured by suitable boulder clays were brick buildings constructed. Similarly where large areas of glacial sands outcrop or where the boulder clay was excessively lime rich (e.g. Chalky Boulder Clay of central Norfolk), medieval brick is rare or absent. This close correspondence between brick buildings and the availability of suitable brick-making materials strongly suggests that bricks were not normally transported very far.

PRE REFORMATION BRICK BUILDINGS OF EAST ANGLIA

FIG. 2



This is further borne out by similarities between the lithology of the bricks and the nearest available source. In general the geological approach supports the conclusions from documentary evidence (Salzman, 1952) that after an initial period, during which large numbers of bricks were imported, bricks were usually made from strictly local materials.

In detail the geological approach may supplement the documentary evidence. Thus, for example, the inclusion of abundant fragments of crumbly sandstone in the bricks of Compton Wynyates (Warwickshire) indicates a boulder clay source rich in Keuper Sandstone fragments; the nearest is at Ettington, 6 miles north west of Compton Wynyates. Similarly the presence of a marine or estuarine fossil in a brick in the Cow Tower at Norwich suggests that bricks were made from estuarine muds, and therefore transported at least 20 miles from the coast up the adjacent river. More detailed field work is required, but these examples serve to illustrate what may be achieved by the geological approach.

(iv) Dating brickwork To the historian, particularly to the architectural historian, the potential value of the geological approach lies in the possibility of dating brickwork. Unfortunately this may be a vain hope. Owing to the re-use of brick, the replacement of weathered brickwork, and imprecision of methods of dating based on architectural styles it is difficult to find sufficient reliably dated brickwork for reference. Modern dating methods such as radio-carbon and palaeomagnetic methods are no more precise and in the majority of cases cannot be used owing either to an insufficiency of carbon or lack of knowledge of the orientation of the brick when burnt.

The nature of the raw material limited the methods used. No methods or materials once used were ever entirely abandoned before the nineteenth century, although different materials and techniques were favoured at different times. The recognition of the introduction of a new technique is probably the best criterion to use for the establishment of a time scale. Since techniques of sand and slop moulding seem to have been used throughout the Middle Ages these are no guide to dating bricks. More significant is that in the mid-fifteenth century, red burning stony boulder clay came to be generally used wherever available; and shortly afterwards vitrified headers were deliberately made from the same material. Detailed discussion of dating problems will be postponed until as many medieval bricks as possible have been examined. We are particularly conscious that there may be regional trends and traditions which deviate from the main pattern. Thus, for example, the early medieval bricks in the Hull region tend to be larger than those made elsewhere (Bilson, 1896); also at ports such as Boston (Mayes 1966), sea coal is more likely to be used than further inland. The final evaluation of these and other factors, such as the addition of sand, cinder, coal or chalk, must await the competion of the field work and laboratory investigations.

Conclusions

Our records indicate that there are about 500 buildings in England which incorporate substantial amounts of Pre-Reformation brick. Two thirds of these are in Essex (146), Suffolk (111), and Norfolk (97). We have examined about a fifth of all the medieval brick buildings in East Anglia and about half of those in Lincolnshire and the Midlands, Oxfordshire, Buckinghamshire and counties south of the Thames still have to be investigated. Though the sampling is small, particularly in Essex (15%) and Suffolk (14%), in all areas consistent results have been obtained.

Superficial deposits appear to have been used exclusively. Up till about 1440 brick colour was not an importand factor in choice of materials, and stoneless estuarine and alluvial silts were used indiscriminately. Though use of these silts continued after 1440, red burning types were then preferred. After this date stony boulder clays and stony alluvium began to be widely used as they were more suitable for the moulded and diaper work which was then in demand.

Distribution of medieval brick is consistent with the known distribution of Pleistocene and Recent deposits. Usually strictly local materials were used, the method of manufacture being largely determined by the physical and chemical characteristics of the raw materials.

Petrography and structure suggest that bricks were usually moulded. Slop moulding was preferred to sand moulding for the most plastic clays. Such bricks were laid out on straw or hay to dry whereas sand moulded bricks were often put directly into a hack. Sand, fluxes or fuels were not usually added.

Although this geological approach has already supplemented present knowledge of medieval brick, more research is needed on regional trends, sources of raw materials and methods of manufacture.

Acknowledgements

We are grateful for the help and encouragement of Professor W. D. Evans and colleagues in the Geology Department at Nottingham; to Mr. Adrian Rundle for identifying the fossils; and to the secretarial and technical staff for assistance in preparing microscope slides, photographs, analyses, diagrams and the typescript. Without this assistance this paper would not have been written.

Most stimulating contributions to this research have resulted from discussions with architects, historians and archaeologists. We are particularly grateful to Mr. Maurice Barley and Dr. Norman Summers of Nottingham University; Mr. Donovan Purcell (Architect, Norwich); the staff of the London Brick Company Limited (Peterborough); Mr. J. S. Gardner (Essex); and many others, all expert in their own fields. Finally we wish to thank the many landowners for their ready willingness to allow us access to their property and for the many interesting discussions.

R. J. Firman, B. Sc., Ph. D., F. G. S.,,
Department of Geology,
The University,
Nottingham.

P. E. Firman, B. Sc. (Mrs. R. J. Firman).
67 Grove Avenue,
Chilwell,
Nottingham.

REFERENCES

BILSON, J., 1896 — The North Bar, Beverley. East Riding Antiquitarian Soc. Trans. vol. IV, p. 47.

BONNELL, G. G. R. and B. BUTTERWORTH, 1950. Clay building bricks of the United Kingdom. Nat. Brick Advis. Council Paper 5, H. M. S. O. London.

BROOKS, F. W., 1939 — A medieval brick yard at Hull. Journ. of the British Arch. Assoc.

BUTTERWORTH, B., 1953 — The properties of Clay Building Materials. Ceramics; a symposium held by the British Ceramic Society.

CURZON of KEDLESTON and H. A. TIPPING, 1929. Tattershall Castle, Lincolnshire. Limited edition of 100 copies. London.

DAVIS, A. D., 1951 — Pottery containing fossil shells. The Antiquaries Journ. vol 31, p. 148.

DOBSON, E., 1882 — A rudimentary treatise on the manufacture of bricks and tiles. 7th Edition. London.

GARDNER, J. S., 1957 — Coggeshall Abbey and its early brickwork. Journ. British Archaeol. Assoc. vol. 18, p. 19-32.

LLOYD, Nathaniel, 1925 — A history of English brick making. London.

MAYES, P., 1965 — A medieval tile kiln at Boston, Lincolnshire. Journ. British Archaeological Assoc. v. 28, p. 86-106.

SALZMAN, L. F., 1952 — Building in England down to 1540. Oxford.

SERLE, A. B. and R. W. GRIMSHAW, 1959. The Chemistry and Physics of Clay. 3rd Edition. London.

SEGER, H. A., 1902 — The collected writings of Hermann August Seger. (Easton Pa.: Chemical Publishing Co.).